Tandem Unzipping and Scrambling Reactions for the Synthesis of Alternating Copolymers by the Cationic Ring-Opening Copolymerization of a Cyclic Acetal and a Cyclic Ester

Motoki Higuchi, Arihiro Kanazawa*, and Sadahito Aoshima*

Department of Macromolecular Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan

Supporting Information Placeholder

ABSTRACT: Cationic copolymerization of different types of monomers, 4-hydroxybutyl vinyl ether (HBVE) and ε-caprolactone (CL), was explored using $EtSO_3H$ as an acid catalyst, producing copolymers with a remarkably wide variety of compositions and sequences. In the initial stage of the reaction, HBVE was unexpectedly isomerized to 2-methyl-1,3-dioxepane (MDOP), followed by concurrent copolymerization of MDOP and CL via active chain end and activated monomer mechanisms, respectively. The compositions and sequences of the copolymers were tunable depending on the initial monomer concentrations. Moreover, a unique method was developed for transforming a copolymer with no CL homosequences into an "alternating" copolymer by removing MDOP from the system using a vacuum pump. This was achieved by the tandem reactions of depolymerization (unzipping) and random transacetalization (scrambling) under thermodynamic control. Specifically, the unzipping of HBVE homosequences proceeded at the oxonium chain end until a nondissociable ester bond emerged next to the chain end, while the scrambling of the main chain via transacetalization transferred mid-chain HBVE homosequences into the polymer chain end.

Simultaneous copolymerization via different mechanisms is an intriguing strategy for synthesizing highly functional polymer materials.[1-12] In particular, copolymers with different types of monomers can be obtained without cumbersome multistep reactions involving purification and isolation. For example, a diblock copolymer of ε-caprolactone (CL) and styrene was produced in one pot via simultaneous (but orthogonal) living coordination ring-opening polymerization (ROP) and nitroxide-mediated radical polymerization using a bifunctional initiator with initiating sites for both polymerizations.[1] A specific type of this method, in which different mechanisms proceed non-orthogonally, has a potential to produce copolymers that are otherwise difficult to obtain. This class of copolymerization includes the copolymerization of vinyl monomers and cyclic monomers via the concurrently occurring vinyl-addition and ring-opening mechanisms[2-8] and chain- and step-growth copolymerization.[9,10] These polymerizations are effective for the synthesis of multiblock-type copolymers via two-way crossover reactions. A wider variety of copolymer sequences and architectures can be produced via this type of copolymerization by completely different intermediates or mechanisms[11,12] because the relative rates of both reactions are tuned independently by changing the reaction conditions, such as the amount of catalyst and the solvent polarity.

The sequence of a copolymer chain is determined by several factors depending on the type of polymerization process. When previously formed polymer chains (backbone) do not collapse throughout a copolymerization process, the sequence is exclusively dominated by the selectivity of the addition of each monomer to the active species, which is related to the monomer reactivity ratio in chain-growth polymerization[13], or by the selectivity of the reaction between the reactive species in step-growth polymerization.[14] By contrast, when polymer chains are collapsed via some reactions, additional factors should be taken into consideration. For example, in copolymerization involving depolymerization (equilibrium copolymerization), various parameters, such as equilibrium constants, are responsible for the resulting sequence of copolymer chains.[15,16] Another example is copolymerization involving random segmental exchanges (scrambling) in main chains, in which copolymer sequences are eventually dominated by a statistical distribution.[17-19] Many studies have been conducted on this type of polymerization based on reversible exchange reactions of "dynamic covalent bonds", such as transesterification[18] and radical exchange reactions.[19] Copolymerization involving this type of reaction is generally not suitable for precisely controlling copolymer sequences due to its random nature.

In this study, we designed a novel nonorthogonal copolymerization system by combining different types of cationically polymerizable monomers, 4-hydroxybutyl vinyl ether (HBVE) and CL, using $EtSO_3H$ as a catalyst (Scheme 1). In general, such copolymerizations via different mechanisms require an astute strategy to avoid interfering with each reaction and to connect different types of polymer

chains. The combination of the cationic polyaddition of vinyl ethers with a hydroxyl group on the side chain (OHVEs)[20,21] and the ROP of cyclic esters via the activated monomer (AM) mechanism[22] can satisfy these demands due to their mechanistic similarity (Scheme S1 in the Supporting Information). Indeed, copolymers containing HBVE and CL units were successfully produced via simultaneous copolymerization; however, HBVE was quantitatively isomerized to 2-methyl-1,3-dioxepane (MDOP) in the very early stage. Therefore, the reaction devised in this study is essentially equivalent to the cationic ring-opening copolymerization of MDOP and CL, which has also not been reported thus far.[23,24] In the copolymerization, MDOP was incorporated into polymer chains even below its equilibrium monomer concentration ($[MDOP]_e$) because depolymerization via unzipping was suppressed due to the generation of MDOP–CL heterosequences. More interestingly, the sequence transformation of a copolymer with no CL homosequences to an "alternating" copolymer was achieved by utilizing unzipping and scrambling reactions during copolymerization.

Scheme 1. Synthesis of poly(HBVE-*co*-CL)s with various sequences via isomerization of HBVE to MDOP and subsequent cationic copolymerization of MDOP and CL.

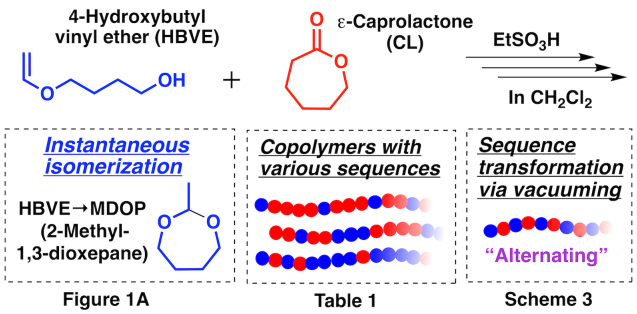


Table 1. Cationic homopolymerization of HBVE and copolymerization of HBVE and CL using $EtSO_3H$ as a catalyst at various monomer concentrations[a]

entry	conc. (M)		time (h)	conv. to polymer (%)[b]		$M_n \times 10^{-3}$ [c]	M_w/M_n[c]	units per block[d]	
	HBVE	CL		HBVE	CL			HBVE	CL
1	0.50	0.50	87	19	98	14.5	1.9	1.0	5.7
2[e]	0.50 (MDOP)	0.50	82	19	99	15.2	1.9	1.0	5.3
3	2.52	1.98	75	51	100	20.8	2.3	1.4	1.8
4	7.20	0.50	22	72	100	8.8	2.7	11	1.0
5	0.50	–	1	0	–	–	–	–	–
6	3.50	–	4	81	–	10.9	2.2	–	–

[a] $[EtSO_3H]_0$ = 5.0 mM, in CH_2Cl_2 (entries 1—3, 5 and 6) or bulk (entry 4) at 30 (entries 1—5) or 0 (entry 6) ºC. [b] Determined by ^1H NMR analysis of quenched reaction mixtures (Figure S1 shows an example). Time-concentration plots of entries 5 and 6 are shown in Figure S2. [c] Determined by GPC (polystyrene standards). The values were calculated from main peaks (GPC chromatograms of entries 4 and 6 are shown in Figure S3). [d] Determined by ^1H NMR analysis (The ^1H NMR spectrum of entry 4 is shown in Figure S4). [e] MDOP was used instead of HBVE.

The cationic copolymerization of HBVE (0.50 M) and CL (0.50 M) was examined using $EtSO_3H$ (5.0 mM) as a catalyst in toluene at 30 ºC, which resulted in a copolymer consisting of both monomer units (entry 1 in Table 1). The number average molecular weight (M_n; no unit because not defined as "molar mass") of the products increased as the polymerization proceeded (Figure 1B) to reach 14.5×10^3 (main peak). Tailing was observed in the low-molecular-weight region of the GPC chromatograms. MALDI-TOF-MS analysis suggested that the main portion of the tailing was composed of cyclic oligomers (Figure S5). The ^1H NMR spectrum of the polymer obtained at 87 h (Figure 1C(i)) had peaks of structures derived from HBVE and CL units and a structure resulting from the crossover reaction from HBVE to CL

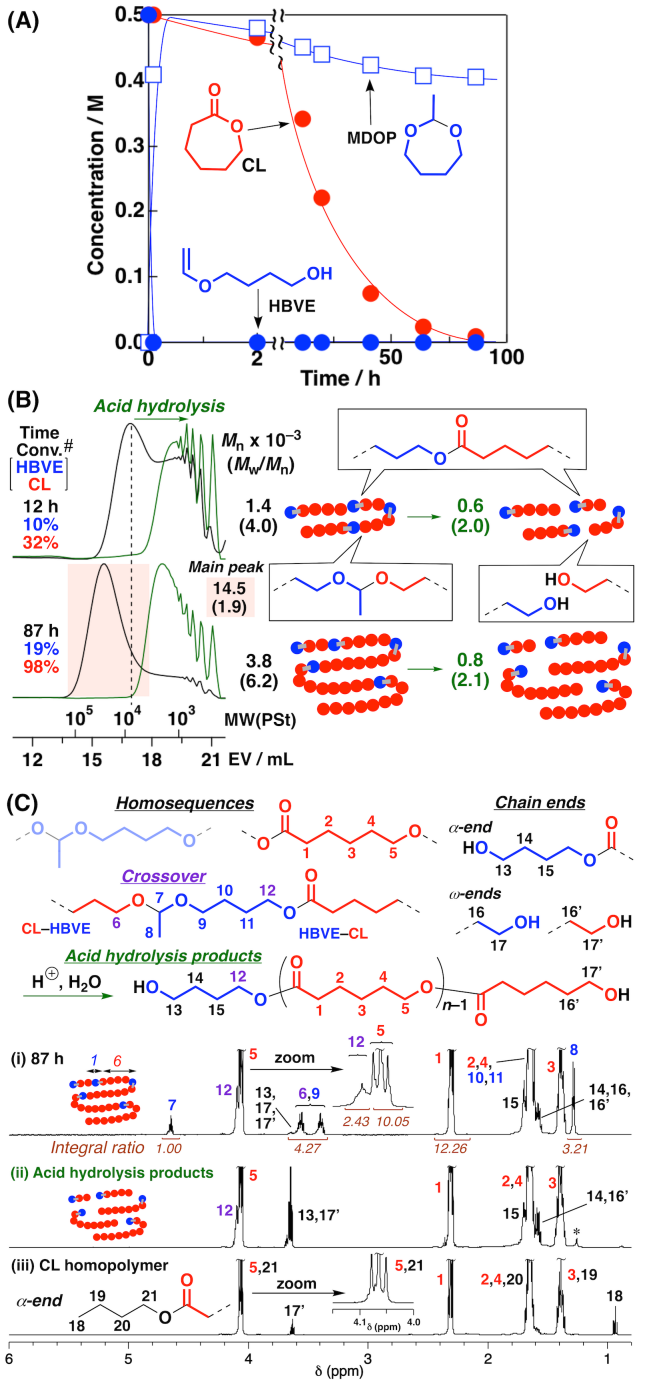


Figure 1. (A) Time-concentration plots for the copolymerization of HBVE and CL [entry 1 in Table 1; determined by ^1H

NMR analysis (Figure S1)], (B) GPC chromatograms of poly(HBVE-*co*-CL)s (black, entry 1 in Table 1) and their acid hydrolysis products (green); # conversion to polymer, and (C) ^{1}H NMR spectra of (i) poly(HBVE-*co*-CL) obtained at 87 h, (ii) its hydrolysis products, and (iii) CL homopolymer [M_n(GPC) = 2.4 × 10^3, M_w/M_n(GPC) = 1.5] [hydrolysis: 0.5 M HCl in H_2O/1,2-dimethoxyethane (1/1 v/v) (0.5wt% polymer) at r.t. for 3 h; in $CDCl_3$ at 30 ºC]; * vaseline.

[peak 12, which is absent in a CL homopolymer (Figure 1C(iii))], suggesting the successful formation of poly(HBVE-*co*-CL). The average numbers of both monomer units per block, calculated from the ratios of ^{1}H NMR integrals, were 1.0/3.8 and 1.0/5.7 for HBVE/CL at 12 h and 87 h, respectively. These results indicate that a copolymer with negligible HBVE homosequences and multiple HBVE–CL and CL–HBVE heterosequences per chain was successfully produced.

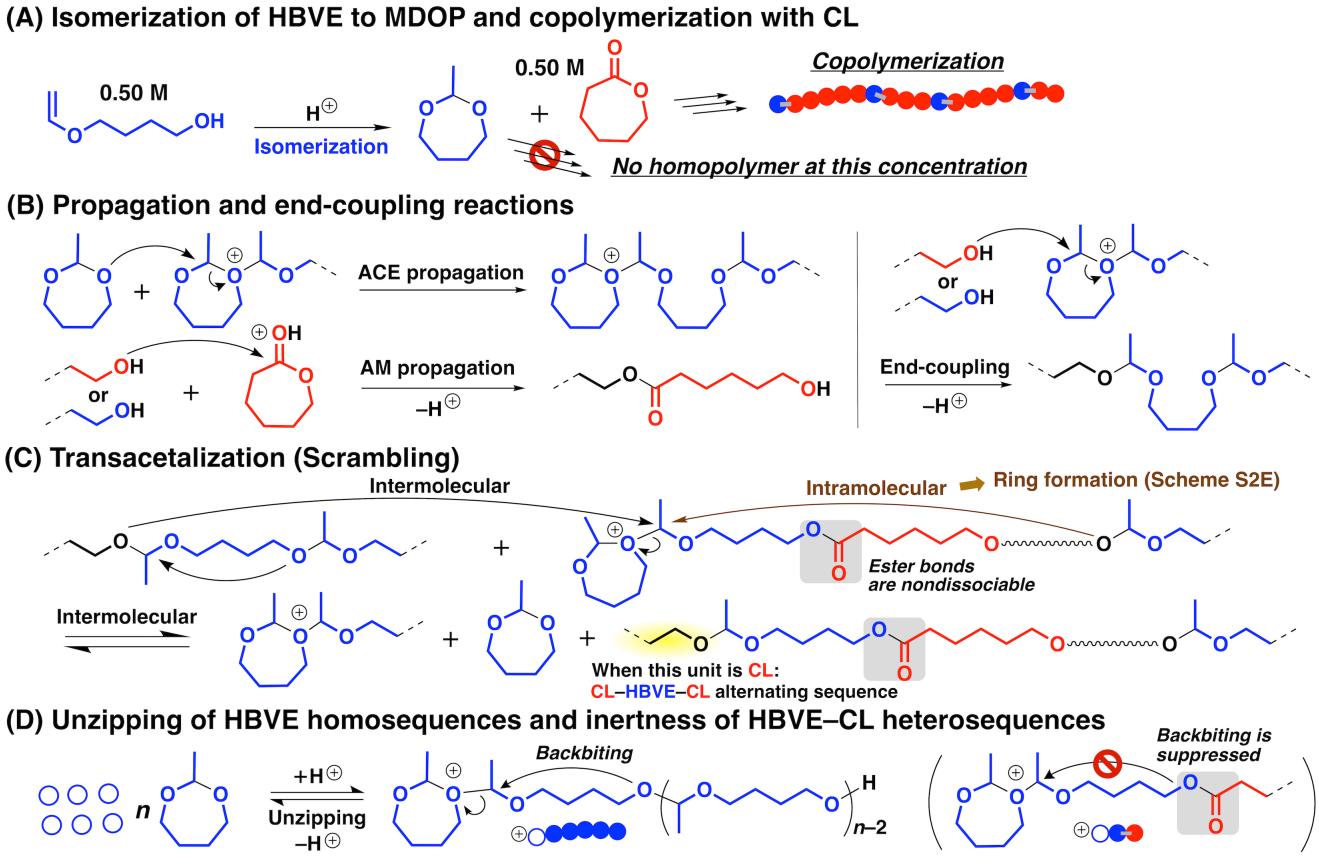
The hydrolysis of the copolymers under acidic conditions was conducted to corroborate the copolymer structure. The ^{1}H NMR spectrum after hydrolysis (Figure 1C(ii)) confirmed the disappearance of the peak of the acetal moiety at 4.6 ppm. The hydrolysis products were composed mainly of CL homosequences with a 4-hydroxybutoxy end group derived from the HBVE moiety, as demonstrated by ^{1}H NMR (Figure 1C(ii)) and MALDI-TOF-MS (Figure S6) analyses. In addition, the clear shift in the GPC chromatograms to the lower region and the significant decrease in M_n values after hydrolysis suggests that the copolymer had not a diblock structure but a multiblock structure with many acetal moieties of CL–HBVE heterosequences. The M_n(GPC) values of the hydrolysis products were 0.6 and 0.8 × 10^3 at 12 h and 87 h, respectively, which is consistent with the above-estimated numbers of units per block.

This copolymerization was found to be essentially identical to the cationic ring-opening copolymerization of MDOP and CL due to the instantaneous isomerization of HBVE to MDOP. Figure 1A presents the changes in the concentrations of HBVE, MDOP, and CL in the copolymerization. HBVE was quantitatively consumed (filled blue circles in Figure 1A), and instead MDOP was formed (open squares) within five minutes. The generated MDOP was gradually consumed in the copolymerization with CL. In addition, the copolymerization of CL with MDOP instead of HBVE under the same conditions, which was conducted to observe differences, resulted in very similar kinetics, molecular weights, and microstructures (entry 2 in Table 1 and Figure S7). Cyclic acetals were also generated in previous reports on the cationic polyaddition of OH-VEs in THF[20,21], although the cyclic acetals were suggested to be unreactive.[25]

The propagation reaction of MDOP is considered to proceed mainly via the active chain end (ACE) mechanism at the oxonium chain ends[26], while the propagation of CL probably proceeds only at the hydroxy ends via the AM mechanism (Scheme 2B, left). In addition, intra- and intermolecular chain end-coupling potentially occurs between the oxonium and hydroxy ends (Scheme 2B, right). The former is likely responsible for the production of a large amount of cyclic oligomers.[27] The existence of both oxonium and hydroxy ends is supported by the end group analysis of HBVE homopolymers (Figure S8). In addition, random segmental exchange via transacetalization[28,29] (scrambling) was found to occur frequently during the copolymerization (Scheme 2C).[30]

The homopolymerization of HBVE under the same conditions as those used for copolymerization produced only MDOP, and no polymers were obtained (Scheme 2A and Figure S2A), unlike the copolymerization with CL. This result is attributed to the lower monomer concentrations used (0.50 M) compared to $[MDOP]_e$ (2.7 M at 30 ºC).[26,31] HBVE homsequences were also not generated in copolymerization conducted at the same concentration of HBVE (0.50 M; entry 1 in Table 1). Therefore, depolymerization (unzipping) via the

Scheme 2. (A) Isomerization of HBVE to MDOP and subsequent cationic copolymerization with CL, (B) propagation and end-coupling reactions, (C) inter- and intramolecular transacetalization in the copolymerization of HBVE and CL[a], and (D) backbiting reactions in the cationic polymerization of HBVE (left) and its suppression in the presence of a CL unit (right).



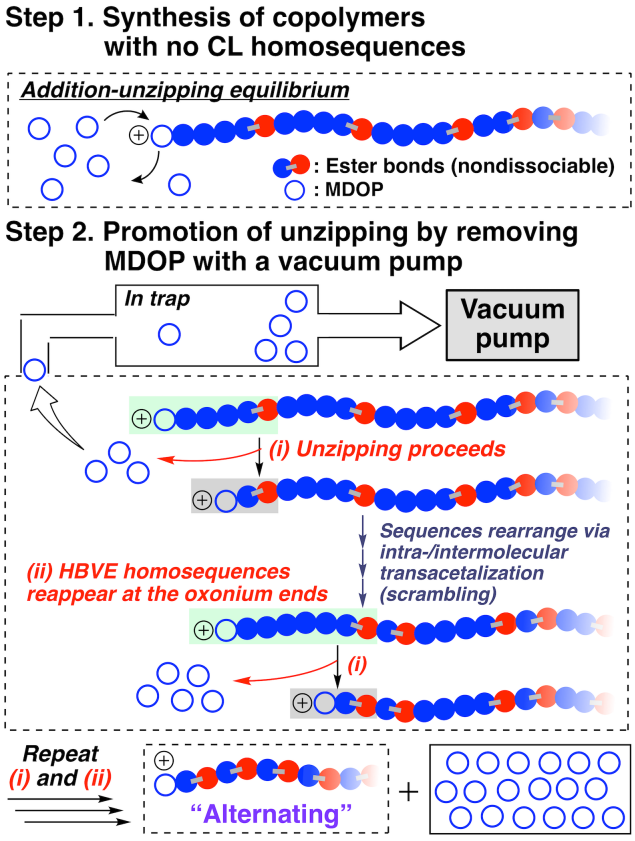
[a] See Scheme S2 for more detailed reaction schemes.

backbiting reaction at the oxonium chain end (Scheme 2D, left), which occurs below the equilibrium concentration of MDOP, was most likely suppressed when an ester bond with a CL unit exists next to the oxonium chain end (Scheme 2D, right). This result is partially similar to the copolymerization of nonhomopolymerizable monomers.[32-36]

Copolymers with various types of sequences were obtained by varying the initial monomer concentrations. In contrast to the aforementioned results, HBVE homopolymers were generated at a high HBVE concentration (entry 6 in Table 1 and Figure S2B, 3.50 M; this value is higher than $[MDOP]_e$), as previously reported.[31] This result suggests that copolymers containing HBVE homosequences can also be produced. Indeed, a multiblock-like copolymer of HBVE and CL was generated at high concentrations of both monomers (entry 3). Moreover, even a copolymer with negligible CL homosequences was obtained at a much higher concentration of HBVE compared to that of CL (entry 4).

Based on the characteristic copolymerization behavior, we designed a unique strategy for producing an "alternating" copolymer as follows: First, the copolymerization is performed at a much smaller concentration of CL than that of HBVE in order to produce a copolymer with no CL homosequences, as in the case of entry 4 in Table 1 (step 1 in Scheme 3). Subsequently, the pressure is reduced using a vacuum pump to

Scheme 3. Strategies for the transformation of poly(HBVE-*co*-CL) with no CL homosequences to poly(HBVE-*alt*-CL) by removing MDOP to outside the system using a vacuum pump.[a]



[a] More detailed reaction mechanisms, which include intra- and intermolecular transacetalization and the formation of not head-to-tail but head-to-head sequences, are shown in Scheme S3 and Figure S13A.

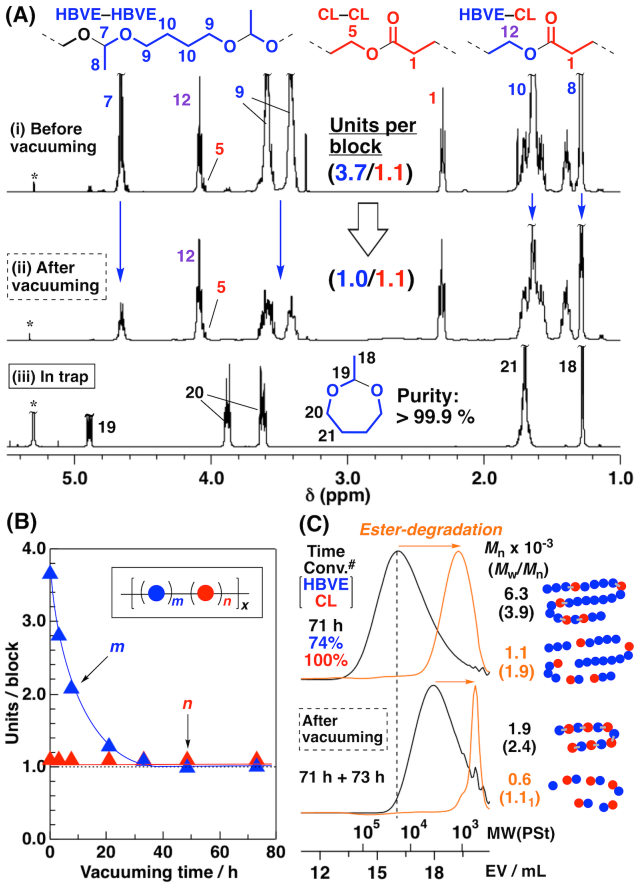


Figure 2. (A) ^{1}H NMR spectra of (i) poly(HBVE-*co*-CL), (ii) the product obtained after vacuuming (a larger spectrum is shown in Figure S10), and (iii) the product in the trap in $CDCl_3$ at 30 ºC; * CH_2Cl_2, (B) vacuuming time-units per block plots for the copolymerization of HBVE and CL (the values were calculated from ^{1}H NMR integrals), and (C) GPC chromatograms of the products before (upper) and after (below) vacuuming (orange: transesterification products); # conversion to polymer {polymerization conditions: $[HBVE]_{total}$ = 6.42 M, $[CL]_{total}$ = 1.42 M, $[EtSO_3H]_{total}$ = 10 mM, $[CH_2Cl_2]_{total}$ = 0.40 M, in bulk at 30 ºC; transesterification: 25 mM $Ti(OBu)_4$ in $BuOAc/CH_2Cl_2$ (8/1 v/v) (0.3 wt% polymer) at 70 ºC for 21 h}.

remove MDOP (b.p. 154 ºC), which is generated via unzipping reactions, from the system (step 2 in Scheme 3). The decrease in MDOP concentration further moves the position of the addition-unzipping equilibrium, which promotes the unzipping of HBVE homosequences at the oxonium chain end (Scheme 2D). Unzipping stops when a CL unit emerges next to the chain end (step 2 *(i)*); however, random sequence redistribution via scrambling occasionally induces the reappearance of HBVE homosequences at the chain end (step 2 *(ii)*), which leads to unzipping again. The repetition of *(i)* and *(ii)* will eventually eliminate all the HBVE homosequences from the polymer chain; hence, a copolymer with "alternating" sequences (acetal and ester units are alternatingly aligned; Scheme S3) will be obtained.

An "alternating" copolymer was successfully generated via the above-described method. In step 1, a copolymer with negligible CL homosequences was produced by keeping the instantaneous concentration of CL low (< 0.5 M) via incremental additions of CL (CL was added three times and quantitatively consumed). The ^{1}H NMR spectrum of the copolymer obtained before vacuuming (Figure 2A(i)) indicates that the peak of CL homosequences (peak 5) is very small, and the average number of units per block was calculated to be 3.7/1.1 for HBVE/CL. Subsequently, vacuuming of the system was conducted, which resulted in a gradual decrease in the volume of the reactants. Accordingly, the average number of HBVE units decreased (Figure 2B), and finally 1.0/1.1 HBVE/CL units per block (Figure 2A(ii)) was reached, suggesting the formation of an "alternating" sequence. The ESI-MS spectrum of the product after vacuuming had peaks with m/z values corresponding to structures consisting of comparable HBVE and CL units, which also supported the "alternating" sequence (Figure S11). The product after vacuuming had a lower M_n value than the original copolymer (Figure 2C, black) due to the removal of the HBVE homosequences. In addition, the MDOP removed via vacuuming was recovered in a trap with a purity of >99.9% (Figure 2A(iii)). DSC measurements showed that the "alternating" copolymer has the T_g value of –70 ºC, which is between the values of HBVE and CL homopolymers (Figure S12).

The ester degradation of the obtained copolymer via transesterification reaction with butyl acetate by $Ti(OBu)_4$ also supported the "alternating" sequence of the copolymer. ^{1}H NMR analyses of the product obtained by transesterification confirmed the quantitative transformation of the original ester moieties into esters with butyl acetate-derived fragments (Figure S13B). The degradation product had an M_n value much lower than that of the original copolymer (Figure 2C, orange). In particular, the low M_n value and narrow MWD of the degradation product (Figure 2C, orange, below) corroborated the "alternating" sequence of the copolymer.[37] Structures derived from the "alternating" sequences were detected in the ESI-MS analysis of the transesterification products (Figure S14)

In conclusion, the copolymerization of HBVE and CL was demonstrated to proceed through the instantaneous isomerization of HBVE to MDOP and the subsequent cationic ring-opening copolymerization of MDOP and CL via concurrently occurring ACE and AM mechanisms. Copolymers with various kinds of sequences were synthesized by changing the initial monomer concentrations. Throughout the copolymerization process, acetal moieties were frequently rearranged via transacetalization and backbiting reactions, while previously formed ester bonds were essentially unchanged. These characteristic reaction behaviors allowed sequence transformation from copolymers with no CL homosequences to "alternating" copolymers by removing MDOP via vacuuming. The removed MDOP, reusable as a monomer, was collected in a trap and had a purity of >99.9%. Using this novel copolymerization system, a variety of poly(acetal-*co*-ester)s with different monomer structures, composition ratios, and sequences can be easily produced, which will contribute to a systematic understanding of the structure-property relationship. Furthermore, the concept of sequence transformation can

be applied to other copolymerization systems with similar reaction behaviors, which will widen the variety of accessible copolymer architectures.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Experimental section, polymerization data, ^{1}H NMR, MALDI-TOF-MS and ESI-MS spectra

AUTHOR INFORMATION

Corresponding Author

*E-mail: aoshima@chem.sci.osaka-u.ac.jp.
*E-mail: kanazawaa11@chem.sci.osaka-u.ac.jp.

Notes

The authors declare no competing financial interest

ACKNOWLEDGMENT

This work was partially supported by JSPS KAKENHI Grant 18J11009, 17H03068, and 18K05217.

REFERENCES

(1) Mecerreyes, D.; Moineau, G.; Dubois, P.; Jérôme, R.; Hedrick, L. J.; Hawker, J. C.; Malmström, E. E.; Trollsas, M. Simultaneous Dual Living Polymerizations: A Novel One-Step Approach to Block and Graft Copolymers. *Angew. Chem. Int. Ed.* **1998**, *37*, 1275.

(2) Okada, M.; Yamashita, Y.; Ishii, Y. Cationic Copolymerization of 1,3-Dioxolane with Styrene. *Makromol. Chem.* **1966**, *94*, 181.

(3) Okada, M.; Yamashita, Y. Cationic Copolymerization of Cyclic Formals and Vinyl Ethers. *Makromol. Chem*. **1969**, *126*, 266.

(4) Simionescu, C. I.; Grigoras, M.; Bicu, E.; Onofrei, G. Spontaneous Copolymerization of 2-Methyl-2-Oxazoline and N-Phenyl Maleimide. *Polym. Bull.* **1985**, *14*, 79.

(5) Rivas, B. L; Pizarro, C.; Canessa, G. Copolymerization via Zwitterion. S. *Polym. Bull*. **1988**, *19*, 123.

(6) Hagiwara, T.; Takeda, M.; Hamana, H.; Narita, T. Copolymerization of *N*-Phenylmaleimide and Propylene Oxide Initiated with Organozinc Compounds. *Macromolecules* **1989**, *22*, 2025.

(7) Yang, H.; Xu, J.; Pispas, S.; Zhang, G. Hybrid Copolymerization of ε-Caprolactone and Methyl Methacrylate. *Macromolecules* **2012**, *45*, 3312.

(8) Kanazawa, A.; Kanaoka, S.; Aoshima, S. Concurrent Cationic Vinyl-Addition and Ring-Opening Copolymerization Using $B(C_6F_5)_3$ as a Catalyst: Copolymerization of Vinyl Ethers and Isobutylene Oxide via Crossover Propagation Reactions. *J. Am. Chem. Soc.* **2013**, *135*, 9330.

(9) Mizutani, M.; Satoh, K.; Kamigaito, M. Metal-Catalyzed Simultaneous Chain- and Step-Growth Radical Polymerization: Marriage of Vinyl Polymers and Polyesters. *J. Am. Chem. Soc.* **2010**, *132*, 7498.

(10) Yang, H; Zhang, J.; Zuo, Y.; Song, Y.; Huang, W.; Jiang, L.; Jiang, Q.; Xue, X.; Jiang, B. Anionic Hybrid Copolymerization via Concurrent Oxa-Michael Addition and Ring-Opening Polymerizations. *Macromol. Chem. Phys.* **2019**, *13*, 1900147.

(11) Aoshima, H.; Uchiyama, M.; Satoh, K.; Kamigaito, M. Interconvertible Living Radical and Cationic Polymerization through Reversible Activation of Dormant Species with Dual Activity. *Angew. Chem. Int. Ed.* **2014**, *53*, 10932.

(12) Higuchi, M.; Kanazawa, A.; Aoshima, S. Concurrent Cationic Vinyl-Addition and Coordination Ring-Opening Copolymerization via Orthogonal Propagation and Transient Merging at the Propagating Chain End. *ACS Macro Lett.* **2017**, *6*, 365.

(13) Mayo, R. F.; Lewis, M. F. Copolymerization. Ⅰ. A Basis for Comparing the Behavior of Monomers in Copolymerization; The Copolymerization of Styrene and Methyl Methacrylate. *J. Am. Chem. Soc.* **1944**, *66*, 1594.

(14) Ueda, M. Sequence Control in One-Step Condensation Polymerization. *Prog. Polym. Sci.* **1999**, *24*, 699.

(15) Szymanski, R. Equilibrium Copolymerization in Ring-Opening Polymerization. In Polymer Science: A Comprehensive Reference; Matyjaszewski, K.; Möller, M. Eds.; Elsevier B.V.: Amsterdam, **2012**; Vol. 4.05.

(16) Lowry, G. G. The Effect of Depropagation on Copolymer Composition. Ⅰ. General Theory for One Depropagating Monomer. *J. Polym. Sci.* **1960**, *42,* 463.

(17) Maeda, T.; Otsuka, H.; Takahara, A. *Prog. Polym. Sci.* **2009**, *34*, 581.

(18) Kotliar, M. A. *J. Polym. Sci.: Macromol. Rev.* **1981**, 16, 367.

(19) Otsuka, H.; Aotani, K.; Higaki, Y.; Takahara, A. Dynamic Covalent Polymers: Reorganizable Polymers with Dynamic Covalent Bonds. *Chem. Commun.* **2002**, *23*, 2838.

(20) Zhang, H.; Ruckenstein, E. Self-Polyaddition of Hydroxyalkyl Vinyl Ethers. *J. Polym. Sci.: Part A: Polym. Chem.* **2000**, *38*, 3751.

(21) Hashimoto, T.; Ishizuka, K.; Umehara, A.; Kodaira, T. Synthesis of Polyacetals with Various Main-Chain Structures by the Self-Polyaddition of Vinyl Ethers with a Hydroxyl Function. *J. Polym. Sci.: Part A: Polym. Chem.* **2002**, *40*, 4053.

(22) Okamoto, Y. Cationic Ring-Opening Polymerization of Lactones in the Presence of Alcohol. *Macromol. Chem., Macromol. Symp.* **1991**, 42, 117.

(23) The copolymerization of cyclic acetal and β-lactone was reported in the past study (reference 24). However, the β-lactone underwent an alkyl-oxygen scission via the ACE mechanism unlike the present study.

(24) Yamashita, Y.; Kondo, S.; Ito, K. Cationic Copolymerization of β,β-Dimethyl-β-propiolactone with 1,3-Dioxolane, 3,3-Bis(chloromethyl)oxacyclobutane, and Styrene. High-Resolution NMR Studies on Sequence Distribution of Copolymers. *Polym. J.* **1970**, *3*, 327.

(25) The results obtained in this study indicate that MDOP is reactive in CH_2Cl_2 in the homopolymerization (Figure S2B) and the copolymerization with CL. The difference likely stems from the solvent used. Indeed, in the homopolymerization of HBVE in THF, which was conducted in this study, the concentration of MDOP was almost steady after the initial stage (Figure S2C), which suggested that MDOP was not involved in the polymerization.

(26) Kubisa, P.; Vairon, P. J. Ring-Opening Polymerization of Cyclic Acetals. In Polymer Science: A Comprehensive Reference; Matyjaszewski, K; Möller, M. Eds.; Elsevier B.V.: Amsterdam, **2012**; Vol. 4.10.

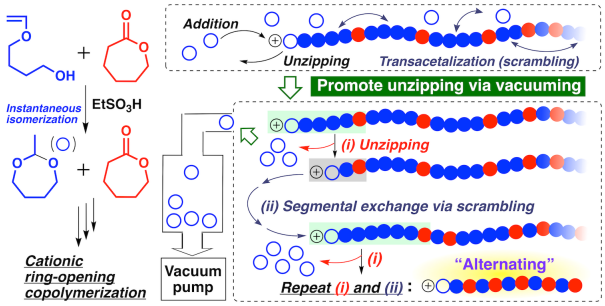
(27) Szymanski, R. Ring-Chain Equilibria in Ring-Opening Polymerization. In Polymer Science: A Comprehensive Reference; Matyjaszewski, K.; Möller, M. Eds.; Elsevier B.V.: Amsterdam, **2012**; Vol. 4.04.

(28) Franta, F.; Kubisa, P.; Ould Kada, S.; Reibel, L. Synthesis of Functionalized Poly(1,3-dioxolane). *Makromol. Chem. Macromol. Symp.* **1992**, *60*, 145.

(29) Chwiatkowska, W.; Kubisa, P.; Penczek, S. Preparation of Living Mono- and Dicationically Growing Polyacetals and Attempts to Prepare Block Copolymers Thereof. *Makromol. Chem*. **1982**, *183*, 753.

(30) This is corroborated by the experimental result that not diblock-type but multiblock copolymers were produced when a fresh supply of MDOP was added at the later stage of the copolymerization (Figure S9, orange). By contrast, transesterification appeared to negligibly occur under the conditions employed (Figure S9, green).

(31) Okada, M.; Yagi, K.; Sumitomo, H. Cationic Polymerization of 2-Methyl-1,3-dioxepane. *Makromol. Chem.* **1973**, *163*, 225.
(32) Ureta, E.; Smid, J.; Szwarc, M. Anionic Copolymerization of Styrene and 1,1-Diphenylethylene *J. Polym. Sci., Part A-1: Polym. Chem.* **1966**, *4*, 2219.
(33) Yuki, H.; Hotta, J.; Okamoto, Y.; Murahashi, S. Anionic Copolymerization of Styrene and 1,1-Diphenylethylene. *Bull. Chem. Soc. Jpn.* **1967**, *40*, 2659.
(34) Inoue, Y.; Koinuma, H.; Tsuruta, T. Copolymerization of Carbon Dioxide and Epoxide. *J. Polym. Sci., Part B: Polym. Lett.* **1969**, *7*, 287.
(35) Ishido, Y.; Aburaki, R.; Kanaoka, S.; Aoshima, S. Well-Defined Alternating Copolymers of Benzaldehydes with Vinyl Ethers: Precision Synthesis by Cationic Copolymerization and Quantitative Degradation to Cinnamaldehydes. *J. Polym. Sci.: Part A: Polym. Chem.* **2010**, *48*, 1838.
(36) Hayashi, K.; Kanazawa, A.; Aoshima, S. Exceptional Copolymerizability of *o*-Phthalaldehyde in Cationic Copolymerization with Vinyl Monomers. *Polym. Chem.*, **2019**, *10*, 3712.
(37) Another point to consider in this strategy is the direction of the dialkoxy structures at acetal moieties because “head-to-head” structures can be generated via transacetalization (Figure S13A). The formation of this structures is confirmed with the obtained alternating-like copolymer by detailed analyses (Figures S13B and S14).



For Table of Contents use only

Tandem Unzipping and Scrambling Reactions for the Synthesis of Alternating Copolymers by the Cationic Ring-Opening Copolymerization of a Cyclic Acetal and a Cyclic Ester

Motoki Higuchi, Arihiro Kanazawa*, and Sadahito Aoshima*