Multifactor Control of Vinyl Monomer Sequence, Molecular Weight, and Tacticity via Iterative Radical Additions and Olefin Metathesis Reactions

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ABSTRACT: Monomer sequence control in terms of a single monomer unit, particularly in vinyl polymers, is one of the largest challenges in polymer chemistry. Furthermore, multifactor control of monomer sequence, molecular weight, and stereoregularity is an ultimate goal. In this work, we propose a strategy to prepare C–C main chain sequence-regulated polymers with controlled molecular weights from vinyl monomers via a combination of iterative atom transfer radical additions and olefin metathesis reactions. This strategy enabled the synthesis of sequence-regulated polymers with exact styrene-acrylate-styrene sequences in the C–C main chains, controlled molecular weights of up to 10^4, and stereoregularities varying with syndiotacticity, isotacticity, and heterotacticity. The utility of this strategy is further demonstrated by the formation of block copolymers consisting of sequence-regulated vinyl polymer segments by combining living ROMP of norbornene derivatives.

INTRODUCTION

An ultimate goal in polymer synthesis is multifactor control of molecular weight, stereochemistry, and monomer sequence because excellent properties and unique functions are expected, as in natural macromolecules such as proteins, which possess perfectly controlled structures.[1] In particular, precise monomer sequence control is one of the largest challenges and will lead to further developments of synthetic polymers for next-generation functional materials.[2–14]

Among various synthetic polymers, vinyl polymers constitute one of the largest families and are prepared by repetitive C–C bond forming reactions via chain-growth mechanisms between propagating chain ends, such as radical, anion, cation, and organometallic species, and vinyl monomers with diverse substituents on the vinyl carbons.[15] The main chain of all vinyl polymers thus consists of only stable C–C bonds, whereas the polymer properties vary widely with the chemical structure of the substituents and can be tuned by the comonomer composition, which is particularly effective for radical polymerization due to a wide variety of polymerizable monomers by radical intermediates. The vinyl monomer sequence is also expected to affect polymer properties and functions. However, in terms of longer-range monomer sequences, diblock, triblock, and even multiblock[16–20] copolymers have been prepared and are used as functional materials, which have properties quite different from those of homopolymers and random copolymers. However, precise monomer sequence control in terms of a single monomer unit is in principle impossible for vinyl polymers, which are generally prepared by chain-growth copolymerization statistically proceeding for the comonomers.[21]

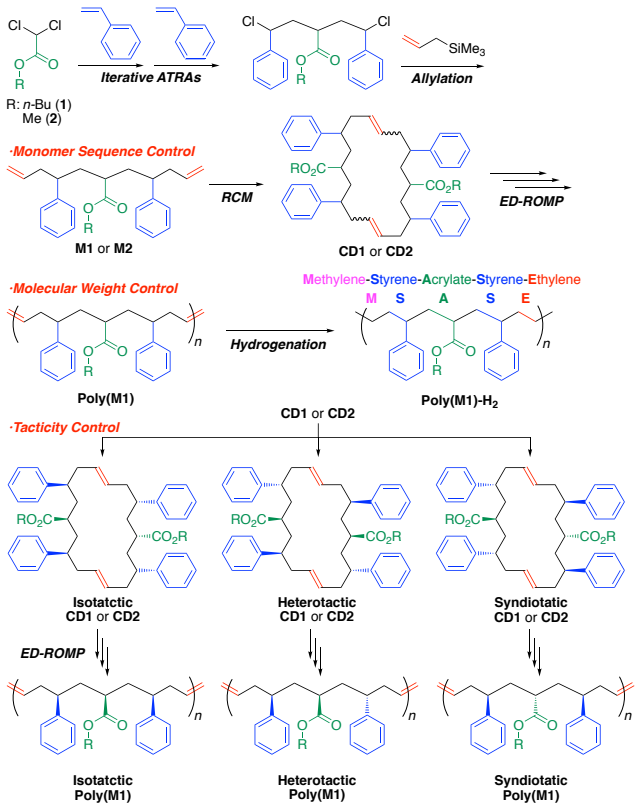
Another efficient carbon-carbon bond forming reaction for polymer synthesis is olefin metathesis,[22] which is applicable to both chain- and step-growth polymerizations, such as ring-opening metathesis polymerization (ROMP)[23,24] and acyclic diene metathesis (ADMET)[25] polymerization, respectively. The latter polymerizes telechelic diene via intermolecular reactions between monomers, oligomers, and polymers, while the former is effective for cyclic olefins mainly with ring strain that react efficiently with metal carbene species at the propagating polymer chain end. Both polymerizations result in polymers linked by C=C bonds, which can be subsequently hydrogenated into the more stable saturated C–C bonds. Indeed, hydrogenated cycloolefin polymers prepared by ROMP of substituted norbornenes and subsequent hydrogenation possess excellent thermal and optical properties, which are difficult to attain by direct polymerization of vinyl monomers.[26] In addition, linear periodically functionalized polyethylene mimics can be obtained by ROMP of substituted cyclooctene[27–29] or ADMET polymerization of functionalized linear telechelic diene[30–32] followed by hydrogenation. Furthermore, living ROMP enables control of the molecular weight of the resulting polymer. A judicious use of metathesis reactions is thus effective for the synthesis of novel C–C main-chain polymers that are directly accessible by polymerization of vinyl monomers. More recently, macrocyclic olefin monomers possessing sequenced ester units have been synthesized and polymerized by ROMP to generate sequence-regulated polyesters.[6,11,13]

One of the most precise sequence controls of vinyl monomers is iterative single unit monomer addition or insertion (SUMI) of vinyl monomers to the chain end of an oligomer.[33–51] This approach is particularly effective for radical addition, which results in stable dormant species and enables isolation

of the products at each step. Iterative radical addition is achieved using an initiating system similar to that for controlled/living radical polymerization or reversible deactivation radical polymerization (RDRP), such as atom transfer radical polymerization (ATRP) and reversible addition-fragmentation chain transfer (RAFT) polymerization, in which stable halides and thioesters are employed as the isolable dormant species.[15] Although the iterative single monomer addition accomplishes perfect sequence control for various vinyl monomers, the precise synthesis becomes harder with an increase in the degree of polymerization due to the iterative processes.

To precisely multiply a short monomer sequence into a long polymer chain, controlled polymerization of the resulting sequence-regulated oligomers is suitable. Therefore, after iterative atom transfer radical additions (ATRAs), we introduced an unconjugated vinyl group and a reactive carbon–chlorine bond at each chain end of the sequence-regulated vinyl oligomers and subsequently polymerized them via metal-catalyzed step-growth radical polymerization to form a main-chain C–C bond along with a pendent C–Cl bond, which is an equivalent structure to the vinyl chloride unit.[36,37] This method has thus constructed perfectly sequence-regulated vinyl polymer structures, but molecular weight control, as well as a high molecular weight polymer, has not been attained due to the slow radical addition to the unconjugated C=C bond and step-growth mechanism.

Scheme 1. Multifactor Control of Vinyl Monomer Sequence, Molecular Weight, and Tacticity by Iterative Atom Transfer Radical Additions (ATRAs), Allylation, Ring-Closing Metathesis (RCM), Entropy-Driven Ring-Opening Metathesis Polymerization (ED-ROMP), and Hydrogenation



Herein, we propose a novel strategy to achieve precisely sequence-regulated vinyl polymers with controlled molecular weights via a combination of iterative ATRAs and ROMP (Scheme 1). This method enables the synthesis of perfectly sequence-regulated polymer mimics with controlled high molecular weights and perfect tacticity from vinyl monomers as starting materials. We thus prepared sequence-regulated trimers using ATRAs twice and then placed olefins at both chain ends by allylation. We were able to then transform the sequence-regulated telechelic diene into the sequence-regulated cyclic olefin via ring-closing metathesis (RCM) and successfully synthesized C–C main-chain sequence-regulated polymers with controlled molecular weights greater than 10^4 via ROMP of the cyclic olefin followed by hydrogenation of the resulting internal olefin. Furthermore, isotactic, syndiotactic, and heterotactic sequence-regulated cyclic olefins were isolated by selective recrystallization and polymerized into multifactor-controlled vinyl polymer mimics with perfectly regulated monomer sequences, controlled molecular weights, and stereoregularity.

RESULTS AND DISCUSSION

Synthesis of Sequence-Regulated Cyclic Olefins via Iterative ATRAs, Allylation, and RCM. The sequence-regulated telechelic diene oligomer (**M1**), which has a symmetrical sequence (OSA_BSO) of one butyl acrylate (A_B) and two styrene (S) units between the terminal olefins (O), was synthesized by iterative ATRAs and subsequent allylation.[37] The first ATRA of styrene to butyl dichloroacetate (ClA_BCl) was conducted using CuCl in the presence of *N*,*N*,*N*′,*N*′′,*N*′′-pentamethyldiethylenetriamine (PMDETA) to form a dimer (ClA_BSCl), which was purified by column chromatography and distillation. Then, the second ATRA of styrene to the dimer using the same catalyst under a slight excess of ClA_BSCl over S selectively resulted in a trimer ($ClSA_BSCl$) because the C–Cl bond adjacent to the A_B unit had a higher reactivity than that adjacent to the S unit and was preferentially activated. The crude product was treated with allyltrimethylsilane in the presence of $TiCl_4$ to yield the sequence-regulated telechelic diene oligomer (OSA_BSO; **M1**) and a byproduct, OSA_BCl, which was generated by allylation of the remaining $ClSA_BCl$ in the crude product. The byproduct (OSA_BCl) was easily removed by column chromatography after being converted to a more polar compound by selective amidation of the activated A_B unit attached to the electron-withdrawing chloride terminal group with 2-aminoethanol, which does not react with an internal A_B unit in **M1** (OSA_BSO).[37] Further purification by distillation resulted in pure **M1** composed of diastereomers and enantiomers (Figure 1A) (total yield 14%).

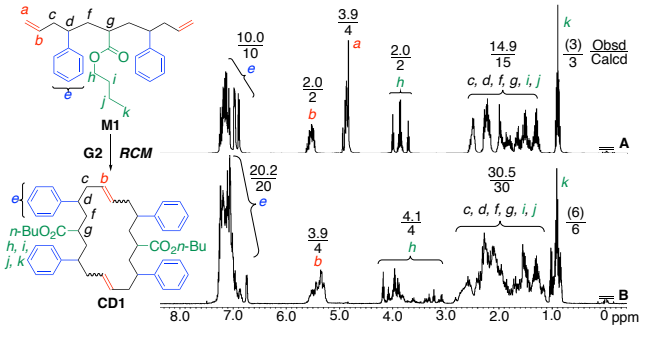


Figure 1. ^{1}H NMR spectra ($CDCl_3$, 25 °C) of M1 (A) and CD1 (B).

To synthesize the sequence-regulated cyclic oligomer, RCM of the telechelic diene oligomer (**M1**) was performed using a second-generation Grubbs catalyst (**G2**) under high dilution of **M1** in toluene at 20 °C ([**M1**]$_0$/[**G2**]$_0$ = 5.0/0.05 mM). The terminal olefin reacted smoothly, and the conversion reached 72% in 20 h. However, contrary to our expectations for the formation of the monomeric cyclic product, the size-exclusion chromatography (SEC) curve of the product shifted to a higher molecular weight while maintaining the unimodal peak with slight tailing (Figure 2A). The main product purified by preparative SEC showed a narrow SEC curve without tailing and only one MALDI-TOF mass peak at 776.9, which is almost identical to the mass (776.2) of the 18-membered cyclic dimer (**CD1**) obtained via olefin-metathesis dimerization of **M1** followed by RCM of the dimer (Figure 2B) (yield 32%). The selective formation of **CD1** is most likely due to the high ring strain of the medium-sized 9-membered cyclic compound. In the ^{1}H NMR spectum, disappearance of the terminal olefin and appearance of the internal olefin were confirmed, although all the peaks of **CD1** were complicated in comparison to those of **M1** due to the diastereomeric mixture of the cyclic products (Figure 1B).

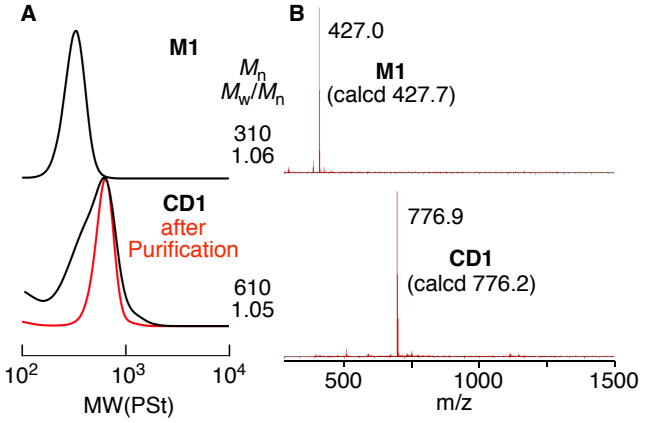


Figure 2. SEC curves (A) and MALDI-TOF-MS spectra (B) of M1 and products obtained by RCM of **M1** ([**M1**]$_0$/[**G2**]$_0$ = 5.0/0.05 mM) in toluene at 20 °C before and after purification by preparative SEC.

During the purification process, we found that some **CD1** was recrystallized. X-ray crystallographic analysis of the single crystal showed that the recrystallized part was indeed the 18-membered cyclic compound, which was a completely sequence-regulated syndiotactic styrene-butyl acrylate-styrene triad linked via *trans* internal olefins (Figure 3A). All ^{1}H NMR peaks of syndiotactic **CD1** were very sharp (Figure 4A) in comparison to those of diastereomeric mixtures (Figure 1B).

We similarly prepared another sequence-regulated telechelic diene oligomer consisting of a styrene-methyl acrylate-styrene sequence (OSA$_M$SO; **M2**) and conducted RCM under similar high-dilution conditions. The obtained products were similarly diastereomeric mixtures of the 18-membered cyclic dimer (**CD2**) of **M2**. Due to the lower solubility of the methyl ester unit in nonpolar organic solvents, the diastereomers were separated into several fractions by silica-gel column chromatography followed by selective recrystallization under different conditions. The three different single crystals obtained were determined to be 18-membered cyclic compounds with syndiotactic, isotactic, and heterotactic sequence-regulated styrene-methyl acrylate-styrene and *trans* internal olefins (Figure 3B–3D). In addition, all peaks in the ^{1}H NMR spectra were sharp and different from each other due to the different tacticity (Figure 4B–4D). The sequence-regulated 18-membered cyclic olefins were thus prepared via a combination of iterative ATRAs and RCM and could be separated into stereoregular isomers by selective recrystallization.

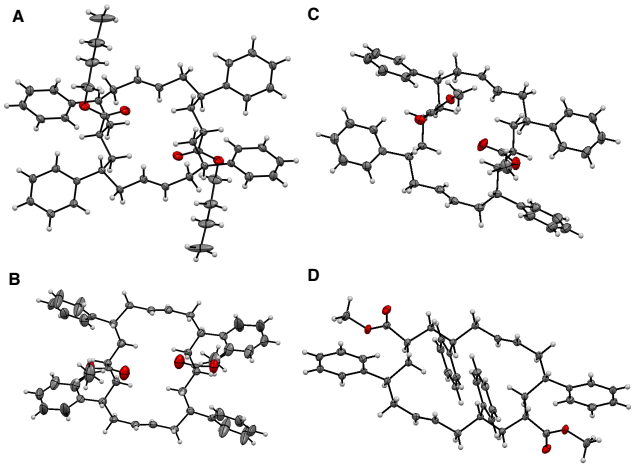


Figure 3. ORTEP diagrams of syndiotactic **CD1** (A), syndiotactic **CD2** (B), heterotactic **CD2** (C), and isotactic **CD2** (D).

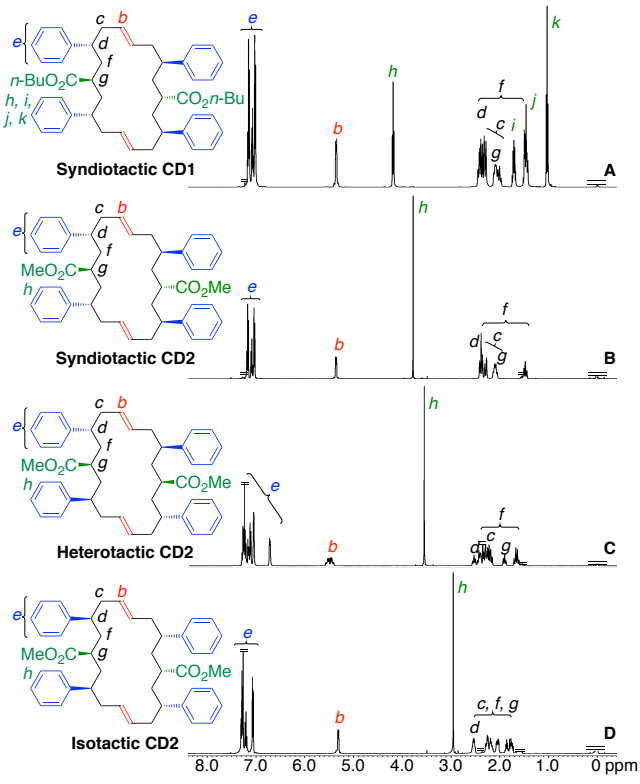


Figure 4. ^{1}H NMR spectra ($CDCl_3$, 25 °C) of syndiotactic **CD1** (A), syndiotactic **CD2** (B), heterotactic **CD2** (C), and isotactic **CD2** (D).

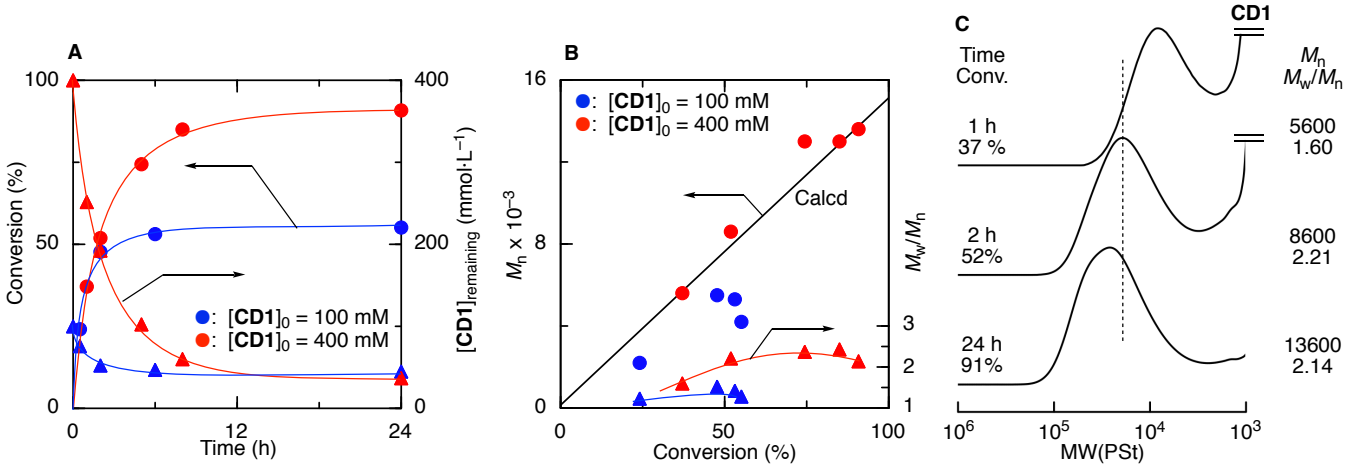


Figure 5. Entropy-driven ring-opening metathesis polymerization (ED-ROMP) of sequence-regulated cyclic oligomer (**CD1**) ([**CD1**]$_0$/[**G2**]$_0$ = 100/5.0 or 400/20 mM) in toluene at 20 °C. (A) Monomer conversion and remaining monomer concentration vs. time plots. (B) M_n and M_w/M_n vs. monomer conversion plots. (C) SEC curves of products obtained at [**CD1**]$_0$/[**G2**]$_0$ = 400/20 mM.

Entropy-Driven ROMP of Sequence-Regulated 18-Membered Cyclic Olefins. ROMP of the diastereomeric mixture of sequence-regulated 18-memblered cyclic olefins (**CD1**) was performed using **G2** in toluene at 20 °C. Although there was almost no ring strain in **CD1**, ROMP occurred (Figure 5). At a lower concentration of **CD1** ([**CD1**]$_0$ = 100 mM), polymerization stopped at approximately 55%, whereas the conversion reached over 90% at a higher concentration ([**CD1**]$_0$ = 400 mM). The final residual monomer concentrations under both conditions were almost the same, approximately 40 mM, indicating that the polymerization reached equilibrium. The polymerization of **CD1** thus proceeded via an entropy-driven ROMP (ED-ROMP) mechanism.[11,13]

The number-average molecular weight (M_n) of the polymers obtained at a higher monomer concentration ([**CD1**]$_0$ = 400 mM) increased in direct proportion to monomer conversion and agreed well with the calculated value assuming that one molecule of the catalyst generates one polymer chain. In addition, the unimodal SEC curves shifted to higher molecular weights, although the molecular weight distribution (MWD) was slightly broad. To obtain a high-molecular-weight polymer, the feed ratio of monomer to catalyst was varied from 20 to 50 by decreasing the concentration of **G2** while holding that of **CD1** constant. The ED-ROMP also proceeded smoothly to result in a high-molecular-weight polymer with M_n greater than 2.5×10^4 (Figure S6).

Figure 6A shows the ^{1}H NMR spectrum of the obtained polymer. The shapes of almost all the peaks were closer to those of the sequence-regulated linear telechelic diene oligomer (**M1** in Figure 1A) than those of the cyclic oligomer (**CD1** in Figure 1B) except for the olefin protons, indicating that the cyclic olefin was polymerized via ROMP to result in linear sequence-regulated polymers with internal olefins. Thus, ED-ROMP of sequence-regulated 18-memblered cyclic olefins enables the synthesis of sequence-regulated polymers with styrene-acrylate-styrene sequences and controlled molecular weights.

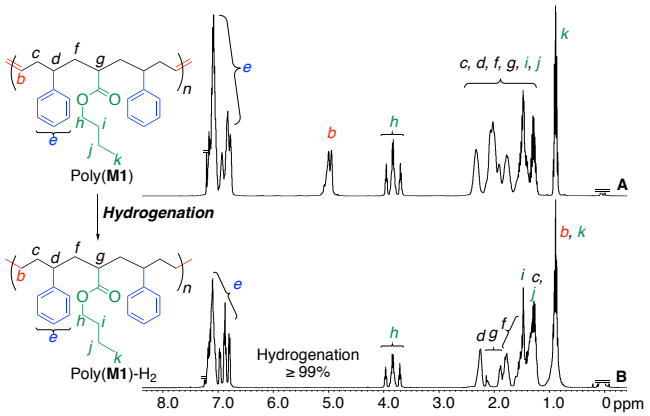


Figure 6. ^{1}H NMR spectra ($CDCl_3$, 55 °C) of poly(**M1**) (M_n = 20700, M_w/M_n = 1.62) (A) and poly(**M1**)-H_2 (M_n = 23000, M_w/M_n = 1.63) (B).

Furthermore, ROMP of a series of three stereoregular sequence-regulated 18-membered cyclic olefins (**CD1**) with a syndiotactic, isotactic, and heterotactic styrene-butyl acrylate-styrene sequence (Figures S4 and S5) was investigated. Isotactic and heterotactic **CD1**s were prepared by transesterification of isotactic and heterotactic **CD2**s, respectively, with butanol. The ROMP of these stereoregular **CD1**s was conducted under the same conditions ([**CD1**]$_0$/[**G2**]$_0$ = 400/8.0 mM) except for syndiotactic **CD1**, which was polymerized under a lower monomer concentration ([**CD1**]$_0$/[**G2**]$_0$= 220/4.4 mM) due to the low solubility in CH_2Cl_2. The isotactic and heterotactic **CD2**s were polymerized at high conversions (≥ 80%) in 24 h to result in high-molecular-weight polymers ($M_n \geq 2.5\times10^4$) (Figure S7), whereas the polymerization of syndiotactic **CD2**s was slow (conversion = 31% in 24 h) to give relatively low-molecular-weight polymers ($M_n = 5.8\times10^3$) due to the low concentrations of the monomer and catalyst. All the ^{1}H NMR spectra of the resulting polymers showed sharp peaks (Figure 7) in comparison to those obtained from diastereomeric mixtures, indicating that stereoregularity was retained during ROMP to give polymers with controlled monomer sequences and molecular weights and high stereoregularity.

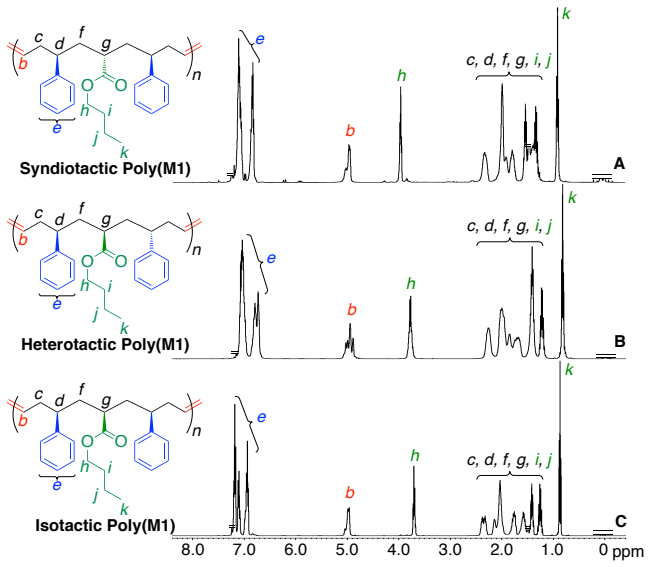


Figure 7. ^{1}H NMR spectra ($CDCl_3$, 55 °C) of syndiotactic poly(**M1**) (M_n = 6400, M_w/M_n = 1.95) (A), heterotactic poly(**M1**) (M_n = 35100, M_w/M_n = 1.95) (B), and isotactic poly(**M1**) (M_n = 33100, M_w/M_n = 1.70) (C).

Hydrogenation to Mimic Sequence-Regulated Vinyl Polymer Structures with Saturated Main C–C Chains. The hydrogenation of internal olefins in the sequence-regulated polymers was examined to mimic the structure of sequence-regulated vinyl polymers, the main chain of which consists of only C–C bonds. Herein, chemical hydrogenation was carried out using *p*-toluenesulfonyl hydrazide in *o*-xylene at 135 °C. As shown in Figure 6B, the olefinic protons at 4.9–5.2 ppm completely disappeared, while only slight changes were observed in the other peaks, indicating nearly complete hydrogenation (>99%). In addition, the SEC curve was almost unchanged, indicating that no chain scission occurred during the reaction (Figure S9). The polymer obtained after hydrogenation thus possesses the completely regulated styrene-butyl acrylate-styrene sequence linked by the additional ethylene-methylene sequence. The isotactic and heterotactic polymers were also successfully hydrogenated.

The thermal properties of the polymers were evaluated by differential scanning calorimetry (DSC). The glass transition temperatures (T_g) of the atactic polymers before and after hydrogenation (M_n = 2.1×10^4 and 2.3×10^4) were 14 and 13 °C, respectively (Figure S10). These values were lower than that of the 2:1 random copolymer of styrene and butyl acrylate with a similar molecular weight (T_g = 40 °C, M_n = 2.6×10^4) prepared by RAFT copolymerization, probably due to the presence of a relatively flexible ethylene-methylene sequence in the repeating units in the sequence-regulated polymers. The effects of tacticity on thermal properties were evaluated for atactic, isotactic, and heterotactic polymers, which have similar molecular weights of approximately 3.2–3.5×10^4, because the molecular weight of the syndiotactic polymer was low (T_g = 2 °C, M_n = 6.4×10^3). The T_g of the isotactic polymer was slightly lower than that of the atactic polymer (10 °C vs. 13 °C), while the heterotactic polymer showed a slightly higher T_g (17 °C) before hydrogenation. However, no additional transitions originating from the stereoregularity were observed for these stereoregular polymers. Similar relationships between the T_g values were also observed for the hydrogenated polymers (Figure S11). Almost no significant dependence of thermal properties on the tacticity can be attributed to the stereoregular styrene-butyl acrylate-styrene triad sequence being isolated by the flexible ethylene-methylene sequence.

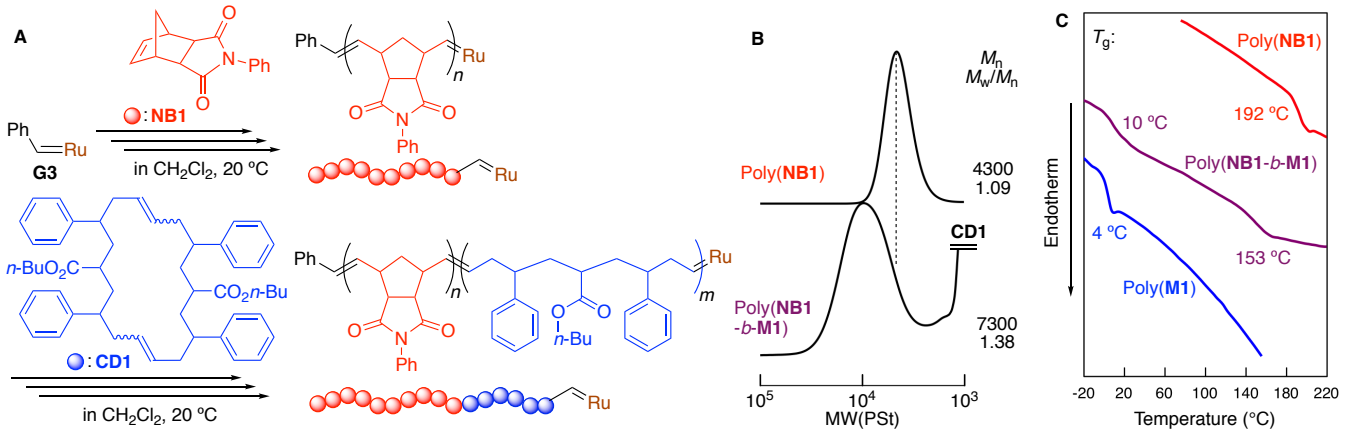


Figure 8. Block copolymerization of norbornene derivative (**NB1**) and sequence-regulated cyclic oligomer (**CD1**) ([**NB1**]$_0$/[**CD1**]$_{add}$/[**G3**]$_0$ = 200/500/20 mM) in CH_2Cl_2 at 20 °C. (A) Scheme. (B) SEC curves of the obtained products. (C) DSC curves of poly(**NB1**), poly(**NB1**-*b*-**M1**), and poly(**M1**).

Block Copolymerization. Block copolymerization of *exo*-*N*-phenylnorbornene-5,6-dicarboximide (**NB1**) and **CD1**, which are strained and strainless monomers, respectively, was examined to synthesize the block copolymer with a sequence-regulated vinyl polymer structure (Figure 8A). We first polymerized **NB1** with a third-generation Grubbs catalyst (**G3**), which is effective for the fast initiation of ROMP,[22] to obtain a polymer with controlled molecular weights and narrow MWDs (Figure 8B). When **NB1** was completely consumed, atactic **CD1** was added as the second monomer. The second polymerization also proceeded to induce a shift of the SEC curve to a higher molecular weight while maintaining the unimodal and narrow MWDs.

Furthermore, the ^{1}H NMR spectrum of the obtained polymers showed characteristic peaks originating from both **NB1** and **CD1** (Figure S11). The number-average degree of polymerization (DP_n(NMR)) of each monomer unit was calculated from the peak intensity ratios of the monomer units to the

initiating phenylene terminal group originating from **G3**. The DP_n(NMR) value was close to DP_n(calcd), which was calculated from the feed ratio of each monomer to **G3** and monomer conversion. The living ROMP chain end of **NB1** thus efficiently initiates ED-ROMP of **CD1** to result in a block copolymer consisting of norbornene derivative segments and sequence-regulated vinyl polymer segments. The DSC of the block copolymer showed two T_g values, at 10 °C and 153 °C (Figure 8C), which correspond to those of poly(**M1**) and poly(**NB1**), respectively, suggesting that microphase separation occurred between the soft and hard segments.

CONCLUSIONS

We developed a novel strategy to prepare precisely sequence-regulated polymers, which consist of only C–C main chains and mimic vinyl polymer structures, by iterative ATRAs of vinyl monomer, allylation, RCM, ROMP, and hydrogenation. The obtained polymers thus have controlled molecular weights greater than 10^4 and can possess stereoregularities varying with isotacticity, syndiotacticity, and heterotacticity. In particular, RCM of the sequence-regulated telechelic diene with styrene-acrylate-styrene sequences under high dilution selectively results in an 18-memebered cyclic dimer of the telechelic diene. This sequence-regulated 18-memebered cyclic olefin undergoes ED-ROMP to afford sequence-regulated polymers with controlled molecular weights and styrene-acrylate-styrene sequences in the main chain. Subsequent hydrogenation results in perfectly sequence-regulated vinyl polymers consisting of styrene-acrylate-styrene-ethylene-methylene sequences. The sequence-regulated polymer segment can be introduced into a block copolymer with norbornene derivatives using sequential monomer addition in living ROMP. This strategy is applicable to the synthesis of precisely sequence-regulated polymers from various vinyl monomers due to the wide applicability of ATRA as well as the robustness of ruthenium-catalyzed ROMP. This method can be used to achieve precise and periodic placement of functional groups in vinyl polymers and will lead to next-generation vinyl polymer materials with excellent properties and unique functions.

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ASSOCIATED CONTENT

Supporting Information

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

Experimental procedures and supplementary data (PDF)
Crystallographic data for syndiotactic **CD1** (CIF), syndiotactic **CD2** (CIF), heterotactic **CD2** (CIF), and isotactic **CD2** (CIF)

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Notes

The authors declare no competing financial interest.

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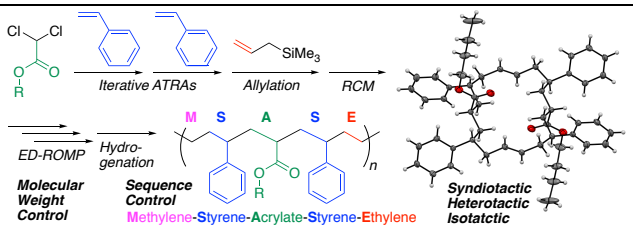

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