

REVIEW

Sequence-controlled polymers via reversible-deactivation radical polymerization

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The development of reversible-deactivation radical polymerization (RDRP) has made a great contribution not only in controlling the molecular weight and terminal structures but also in the precise synthesis of copolymers. An additional design for controlled propagation via RDRP could lead to control of the order of repeating units, that is, the ‘sequence control’, which has been recognized as the ultimate control of precision polymerizations. In this review article, some concepts and methodologies are summarized for synthesizing sequence-controlled polymers based on RDRP.

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REVERSIBLE-DEACTIVATION RADICAL POLYMERIZATION

Radical polymerization is more practical than ionic polymerizations because a variety of monomers can be copolymerized without the need to protect the polar pendant group due to active and neutral propagation species. In addition, the development of reversible-deactivation radical polymerization (RDRP),¹ which is also called controlled/living radical polymerization, has opened the door for the precise synthesis of ‘uniform’ polymers with controlled molecular weights and terminal groups and the precise connection of different segments, as symbolized by block copolymers and graft copolymers. The growing radical propagating species (i.e., active species) is reversibly deactivated with a leaving group to produce a dormant species, and a stimulus then triggers the activation of the dormant species to generate a lower concentration of radical species than that under free radical polymerization conditions. The following three representative systems have been developed for RDRP (Figure 1): nitroxide-mediated polymerization;^{2,3} metal-catalyzed living radical polymerization^{4–6} or atom transfer radical polymerization (ATRP)^{7,8} and reversible addition fragmentation chain transfer polymerization (RAFT).^{9,10} The advantage of these polymerizations is that special techniques are not required; thus, researchers in various fields can use them according to their purpose. Therefore, it is now easy to incorporate a variety of pendant groups onto not only simple linear chains but also armed or branched chains according to a desired property and functionality. As described below, a significant feature of RDRP is the uniform composition distribution among the resultant chains for copolymerization with different reactivity comonomers, which is in sharp contrast to free radical polymerization that results in various compositions. Notably, the inherent reactivity ratio cannot be

changed even with RDRP because the propagating species is basically the same as in free radical polymerization.

SEQUENCE IN POLYMER SCIENCE

Peptides, which are representative polymers in nature, can be called copolymers that consist of a variety of amino acid units. Surprisingly, although as many as 20 kinds of amino acids have been used as comonomers, the addition order for the propagation is perfectly programmed under the central dogma from DNA.¹¹ The order of amino acid residues (i.e., pendant groups), that is, the ‘sequence’, is essential for determining three-dimensional structures and their functions. However, the sequence of artificial copolymers is generally unregulated even in the copolymerization of only two kinds of monomers, except for an AB alternating sequence with a special combination.¹²

We can easily design the pendant for some types of monomers (acrylates, acrylamides, styrenes, vinyl ethers, etc.) for functionalization, and thus the sequence control of copolymers has attracted attention for a long time. The structural similarity to peptides consisting of a backbone (main chain) and pendant groups (side chains) is also the reason for the interest from polymer chemists (Figure 2). It may be extremely difficult to realize an artificial template system, such as the central dogma in nature; however, there is no doubt that RDRP that allows controlled propagation without irreversible deactivation can be a base system for approaching sequence control for carbon-based polymers. Sequence-controlled polymers could change the concept of functional materials in various fields that involve synthetic polymers.^{13–16} In this review article, we describe the recent advances in sequence-controlled copolymers using the RDRP system.

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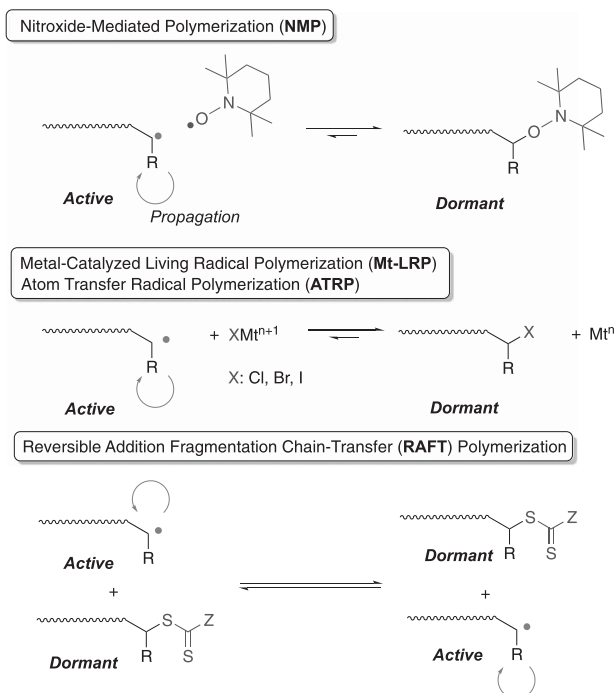


Figure 1 Reversible-deactivation in NMP, Mt-LRP, ATRP and RAFT polymerization. Mt-LRP, metal-catalyzed living radical polymerization; NMP, nitroxide-mediated polymerization. A full color version of this figure is available at *Polymer Journal* online.

MULTIBLOCK COPOLYMERS VIA SEQUENTIAL MONOMER ADDITION

In established living anionic polymerizations, the propagation species is really ‘living’, and no unfavorable side reactions occur even after the monomer is consumed. Thus, the addition of another monomer when the first polymerization is completed allows initiation from the terminal of the first polymer to prepare block copolymers in one pot. However, in the case of a radical process, such a method does not proceed well because the possibility of irreversible deactivation, such as radical-radical coupling termination, relatively increases, as the polymerization proceeds to make the monomer concentration lower. Thus, the typical methodology for the synthesis of block copolymers with RDPD is that once polymers carrying a leaving group are synthesized at the earlier or middle stage where the monomer remains plentiful, the purified polymer is used as the macroinitiator for the second polymerization.

Under optimized conditions in highly controlled RDPD systems, almost perfect suppression of irreversible deactivation becomes possible even after the monomer conversion reaches 100%. For example, Perrier and co-workers¹⁷ performed the synthesis of an icosablock copolymer consisting of some types of short alkyl acrylamide segments (4-acryloylmorpholine (NAM), *N,N*-diethylacrylamide and *N,N*-dimethylacrylamide) via iterative RAFT oligomerization with a water-soluble macro chain transfer agent, which was derived from a low molecular weight chain transfer agent (i.e., 2-(((butylthio)-carbonothioyl)thio)propanoic acid) through RAFT polymerization of NAM in conjunction with an azo-based initiator (VA-044) in water at 70 °C (Figure 3). In this study, the aqueous condition is crucial for approaching continuous propagation via repetitive monomer addition with a higher propagation rate in water. This condition allows faster polymerization without a concomitant loss of living polymerization

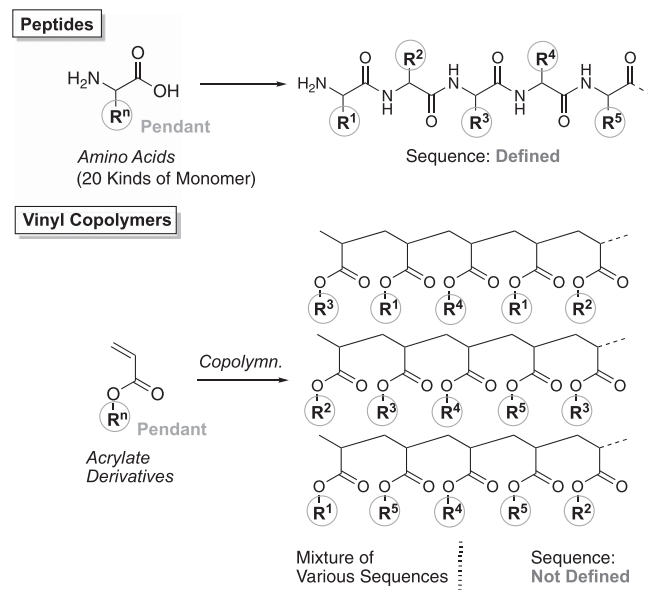


Figure 2 Comparison between peptides and vinyl copolymers in terms of sequence. A full color version of this figure is available at *Polymer Journal* online.

feature, and indeed the initiator with a lower 10-h half-life decomposition temperature (44 °C in water) is almost fully decomposed in 2 h at 70 °C. Although there is a problem with the accuracy regarding the number of inserted monomers due to the limitation by Poisson distribution,¹⁸ an icosablock copolymer can be synthesized by repeating the addition of three equivalent monomers of various pendant groups 20 times. Similar multiblock copolymers of acrylates have been synthesized via aqueous single-electron transfer living radical polymerization¹⁹ or Cu-mediated photopolymerization.^{20–22}

GRADIENT COPOLYMERS VIA TANDEM MONOMER TRANSFORMATION

When two kinds of the same monomer derivatives (i.e., alkyl methacrylates) are copolymerized, the sequence of the resultant copolymer is totally random regardless of whether the polymerization is performed with RDRP or not, as the radical species from the two comonomers show no preference for the next monomer. However, when one monomer is gradually added into the polymerization of another monomer, there is a big difference in the resultant composition distribution between RDRP and free radical polymerization: a gradient sequence can be obtained in the former under the control of the addition speed, whereas a mixture of chains with various composition ratios was observed in the latter case (Figure 4a).²³ The intentional control of the existing comonomer concentration for the RDRP process without irreversible deactivation of the growing end allows a uniform sequence between resultant chains.

A unique approach to synthesize such gradient copolymers using another method has been reported. Central to this method is the control of the concurrent transformation of the monomer into another during RDRP. If the transformation rate matches the propagation and if the *in situ* transformed monomer exhibits the same reactivity as the starting monomer for the copolymerization, copolymers having a gradient sequence can be obtained. Such a tandem process of RDRP along with monomer transformation was realized with the ruthenium-catalyzed living radical polymerization

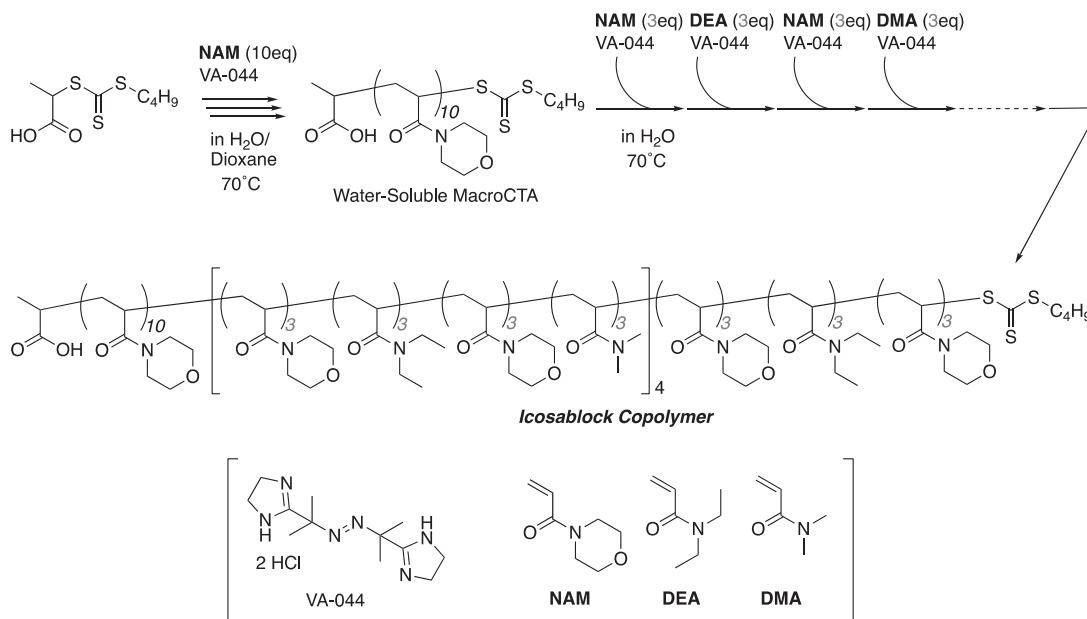


Figure 3 Synthesis of an icosablock copolymer via iterative RAFT oligomerization using three types of acrylamide. A full color version of this figure is available at *Polymer Journal* online.

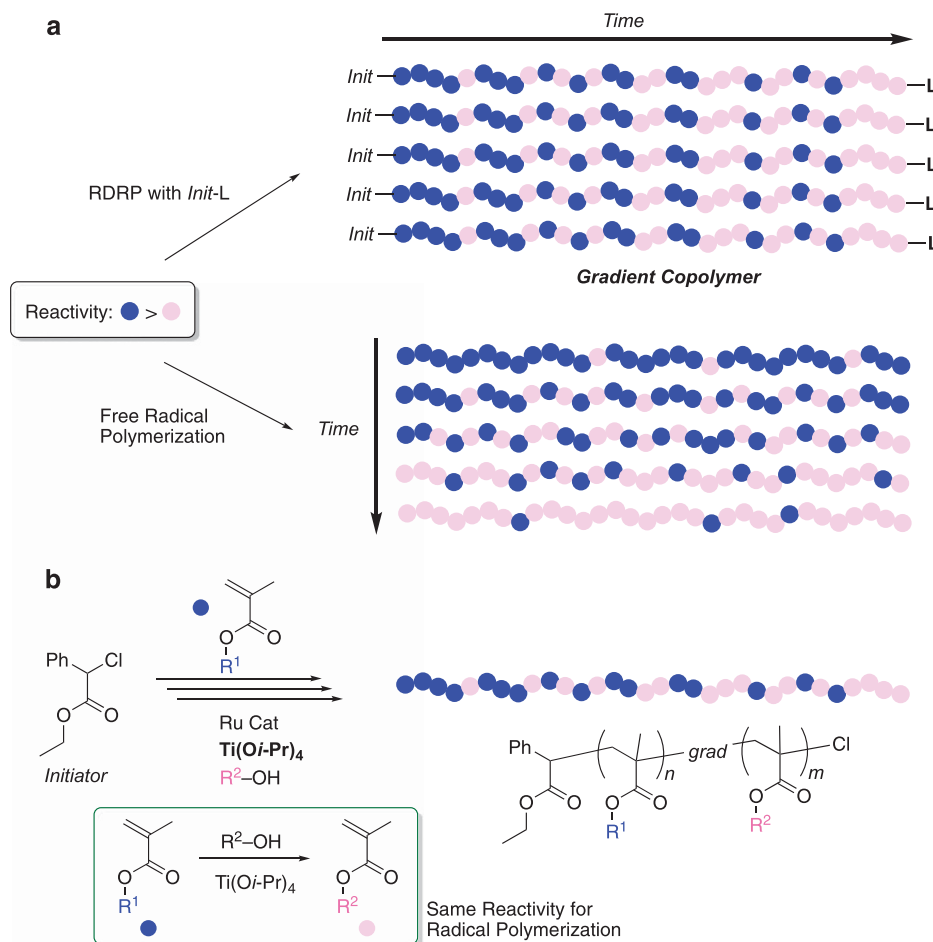


Figure 4 (a) RDRP vs free radical polymerization for the copolymerization of two monomers that exhibit different reactivities. The copolymer image for free radical polymerization is not correct in terms of chain length (i.e., molecular weight) because it is not actually controlled; (b) synthesis of a gradient copolymer via tandem catalysis of Ru-LRP and *in situ* transesterification by Ti(Oi-Pr)₄.

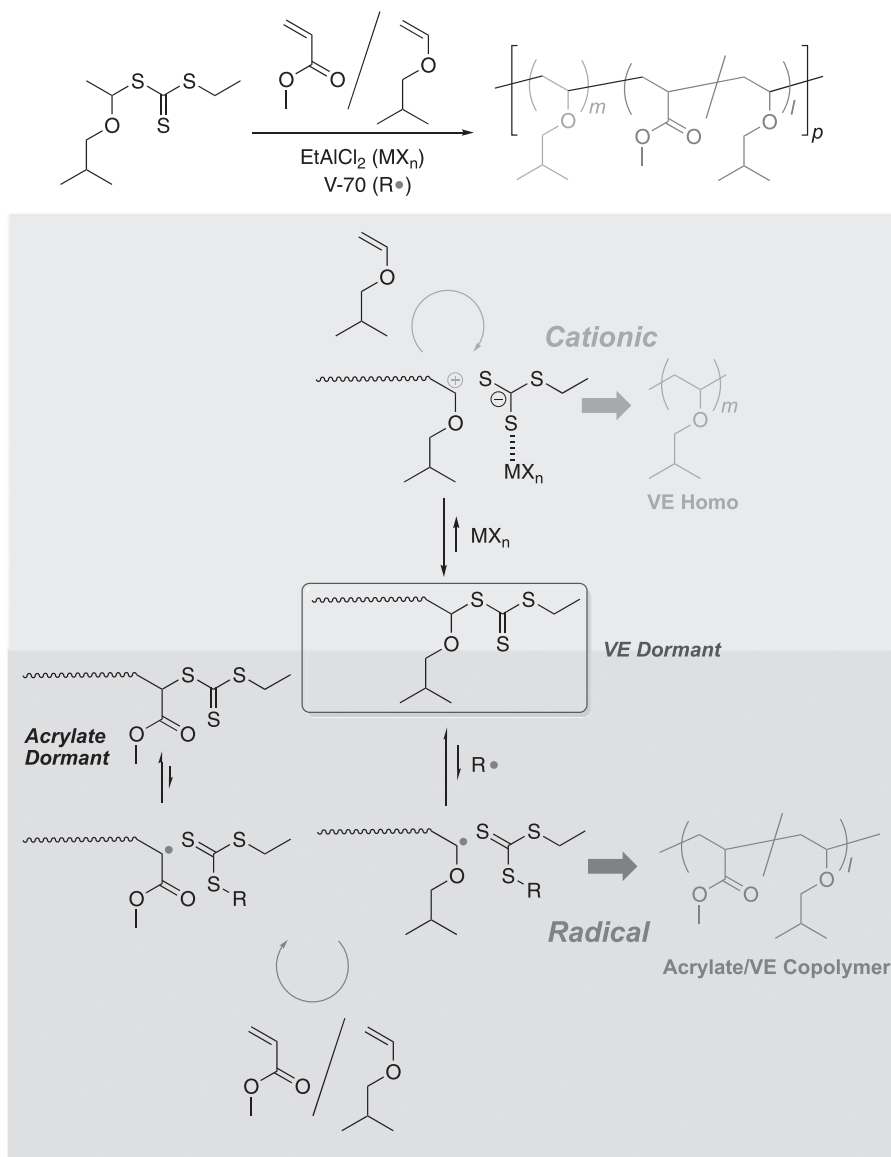


Figure 5 Interconvertible living cationic polymerization and RAFT polymerization of isobutyl vinyl ether and methyl acrylate. A full color version of this figure is available at *Polymer Journal* online.

(Ru-LRP) of methacrylate in conjunction with a metal alkoxide (e.g., $\text{Ti}(\text{O}i\text{-Pr})_4$) in the presence of an alcohol (Figure 4b).^{24–26} In this process, the metal alkoxide acts as the cocatalyst for Ru-LRP and concurrently as the catalyst for the transesterification. The transesterification occurs for the remaining methacrylate monomer with the alcohol under the metal alkoxide catalysis to generate the corresponding methacrylate at a moderate rate, which leads to a gradual change in the monomer composition. The produced polymer does not undergo the transesterification, which is likely due to the steric hindrance. The synchronized rate control is essential, and various functional groups can be incorporated by selecting different alcohols.^{27–30}

UNIQUE COPOLYMERS VIA CONCURRENT TRANSFORMATION OF ACTIVE SPECIES

Different active species can be generated from identical dormant species according to the stimulus. For example, a carbon–halogen bond that is activated into a carbocationic species via Lewis acid

catalysis for living cationic polymerization^{31,32} is also available as the dormant species in conjunction with one-electron redox catalysis for metal-catalyzed living radical polymerization^{4,5} or ATRP.^{7,8} If such different catalysis simultaneously works for the same leaving group to control two different polymerizations (e.g., radical and ionic) in one pot, a unique sequence could be expected beyond the limitation of the inherent reactivity ratios in radical polymerization. There have been some examples of terminal transformation after polymerization for syntheses of block copolymers using different mechanisms;³³ however, concurrent transformation during polymerization is more challenging.

Satoh and co-workers³⁴ recently achieved interconversion between a radical and cationic species with a RAFT-based leaving group in conjunction with 2,2'-azobis(4-methoxy-2,4-dimethylvaleronitrile) (V-70) and EtAlCl_2 to prepare a unique copolymer of methyl acrylate (MA) and isobutyl vinyl ether (Figure 5). In this study, the dormant vinyl ether is the key to realizing the interconversion of the two polymerizations: an MA-rich copolymer segment is formed via

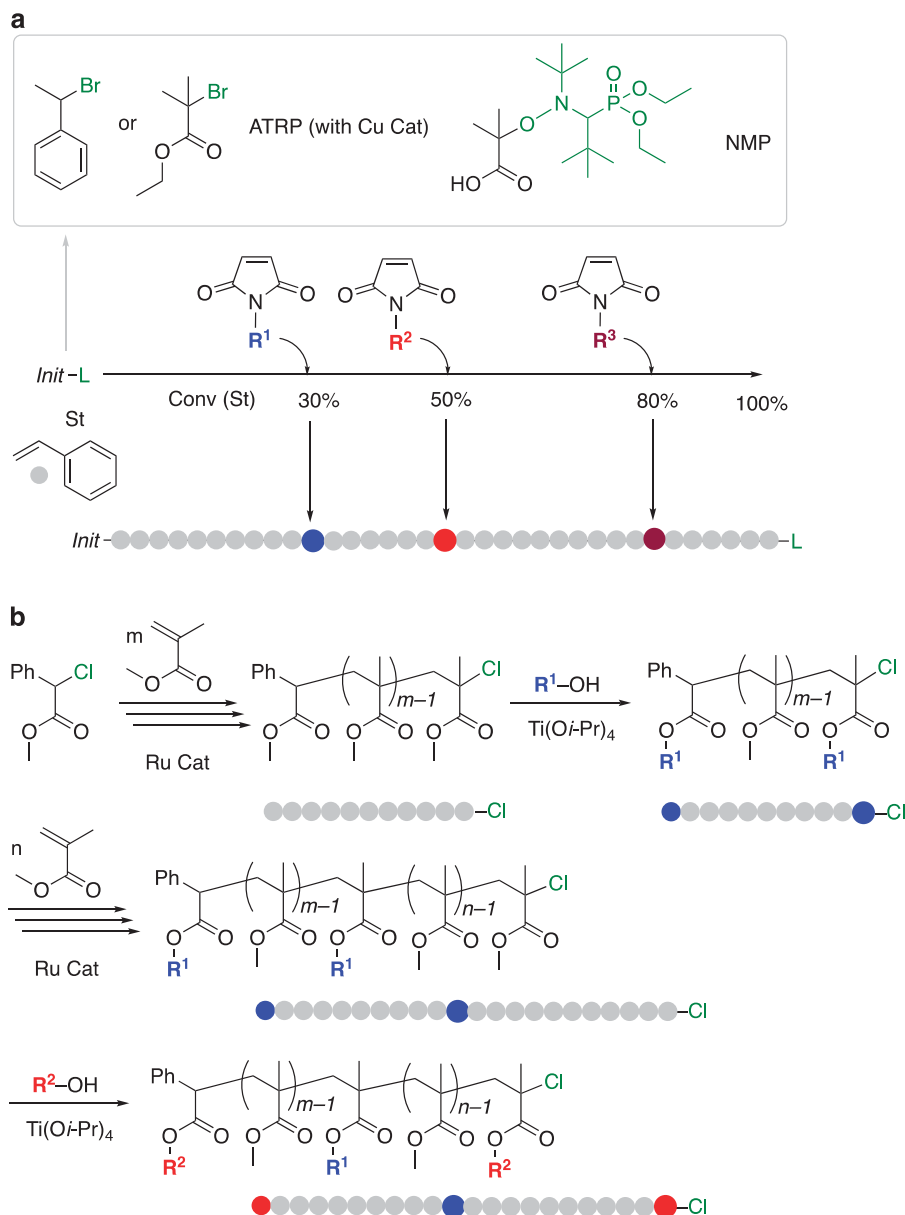


Figure 6 Pinpoint functionalization with RDRP: (a) addition of the maleimide monomer during RDRP of styrene and (b) selective transesterification of terminal methacrylate units for Ru-LRP.

copolymerization of MA and isobutyl vinyl ether during radical propagation, whereas an isobutyl vinyl ether homo segment is formed during cationic propagation. Eventually, some interconversions allow the syntheses of multiblock sequences of the two types of segment. Recently, the researchers controlled various sequence distributions by tuning the acidity of a combined Lewis acid for the RAFT-based dual radical and cationic polymerization.³⁵

PINPOINT-FUNCTIONALIZED COPOLYMERS

It has been known that radical copolymerization of special comonomer pairs consisting of an electron-rich monomer (e.g., vinyl ether and styrene) and an electron-poor monomer (e.g., maleic anhydride and maleimide (MI)) produces an alternating sequence via a free radical polymerization process.¹² In the ideal case of this alternating copolymerization, the composition ratio of the resultant copolymer becomes approximately 50% regardless of the injection ratio during

the early stage of the polymerization. This means that the minor monomer selectively propagates over the primarily existing monomer even though there is a big difference in the injected amounts of the comonomers.

Lutz and co-workers^{36–44} noticed the crossover propagation feature of the alternating copolymerization for achieving local functionalization of a polymer chain using RDRP (Figure 6a). In this approach, styrene or the derivative is polymerized with RDRP (ATRP or NMP), and a slight excess of an MI derivative is added to the growing chains during the RDRP for pinpoint insertion. At the moment of the addition, the MI monomer is immediately incorporated into the growing polystyrene chain via preferential crossover propagation, followed by a homo propagation of residual styrene monomers. In this methodology, it is impossible to incorporate only one unit of MI because of the inherent statistical growth. However, uniform growth for the main polymerization of styrene to produce a narrow molecular

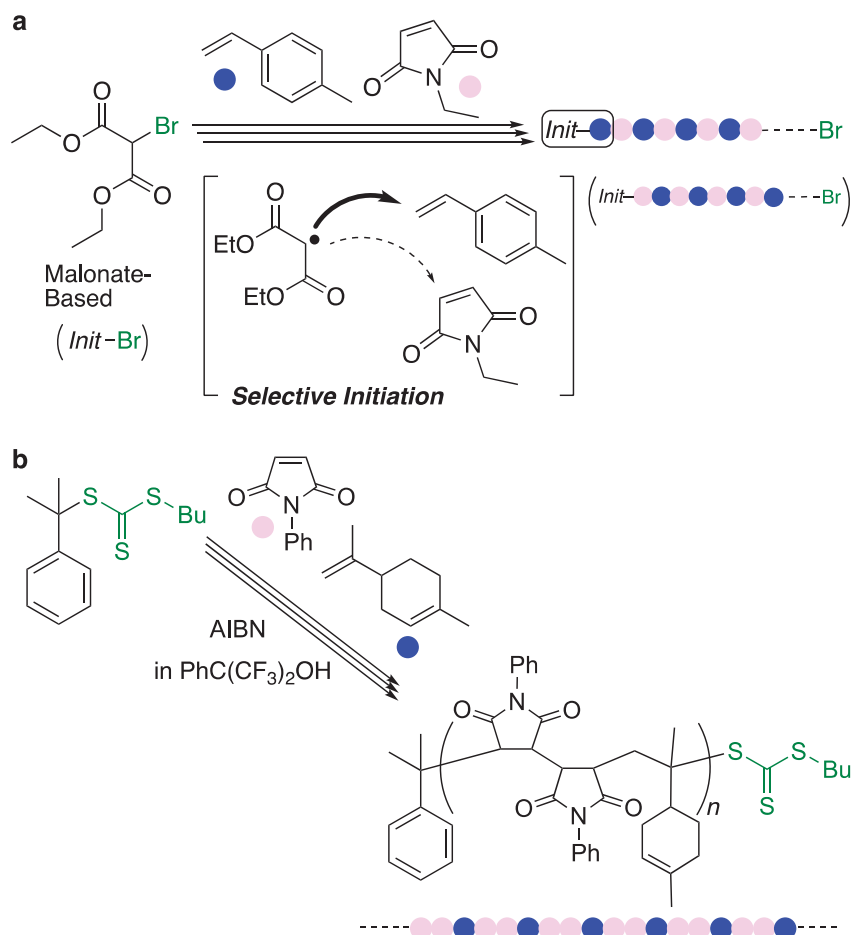


Figure 7 Sequence control with RDRP based on alternating copolymerization: (a) control of the AB alternating sequence via selective initiation with Ru-LRP and (b) control of the AAB sequence with RAFT polymerization in $\text{PhC}(\text{CF}_3)_2\text{OH}$.

weight distribution allows pinpoint functionalization at specific locations on the polystyrene chain, which can be controlled by the styrene conversion at the time of addition and the final conversion. Various functional or reactive groups can be embedded through the pendant group of styrene or MI, and indeed, some unique structures and/or functions have been demonstrated with the methodology, such as pinpoint-functionalized polyelectrolytes,⁴⁵ the construction of unique topologies^{46,47} and a sugar array.⁴⁸

In living anionic polymerization, diphenyl ethylene or its derivatives are very useful as capping agents for pinpoint functionalization. They are not homo-polymerizable; however, the resultant anion is capable of initiating the polymerization of other monomers.⁴⁹ Such useful capping agents have not been reported for RDRP. However, for the halogen-capped poly(methyl methacrylate) chain synthesized by Ru-LRP, the terminal ester pendant selectively undergoes a transesterification with $\text{Ti}(\text{O}i\text{-Pr})_4$ due to the different electronic and steric environment from other pendants.⁵⁰ After the selective functionalization with an alcohol (ROH), the terminal halogen can be activated to restart Ru-LRP of MMA; thus, the pinpoint functionalization of poly(methyl methacrylate) can be realized (Figure 6b).

ALTERNATING COPOLYMERS UTILIZING INHERENT CROSSOVER PROPAGATION

The alternating copolymerization of comonomers with largely different electron densities¹² is an interesting phenomenon for aiming for

sequence control of vinyl polymers, as the selectivities of the two active species in the two monomers are secured to some extent. However, the detailed mechanism or accuracy of the alternating sequence is still unknown. By utilizing RDRP for the alternating copolymerization, the sequence can be analyzed with MALDI-TOF-MS because the molecular weight and terminal groups can be controlled. In this case, control of the selectivity of the first unit adjacent to the initiator moiety and of the final one to the halogen could simplify the resultant peak pattern to make the analysis easier.

For Ru-LRP, a malonate-based initiator that carries two electron-withdrawing groups (esters) showed high selectivity for the initiation of the electron-rich monomer (styrene) over the electron-poor monomer (MI) as well as a high initiation efficiency (Figure 7a).⁵¹ Indeed, the use of the initiator facilitated the analyses of the sequences of the copolymers of *para*-methyl styrene and alkyl maleimide, which revealed that imperfect alternating propagation also occurred even though the monomer composition ratio was 1:1.

Kamigaito's group found that a fluoroalcohol solvent affects the copolymerization of phenylmaleimide and *D*-limonene to induce a very unique periodic sequence, a repetitive AAB sequence (A: phenylmaleimide, B: *D*-limonene) (Figure 7b).⁵² Each solvent molecule interacts with two MI molecules, which was supported by the model compound analysis, and the couple behave as one electron-withdrawing monomer to lead to the unique sequence. Importantly, the alternating propagation was realized even with RAFT

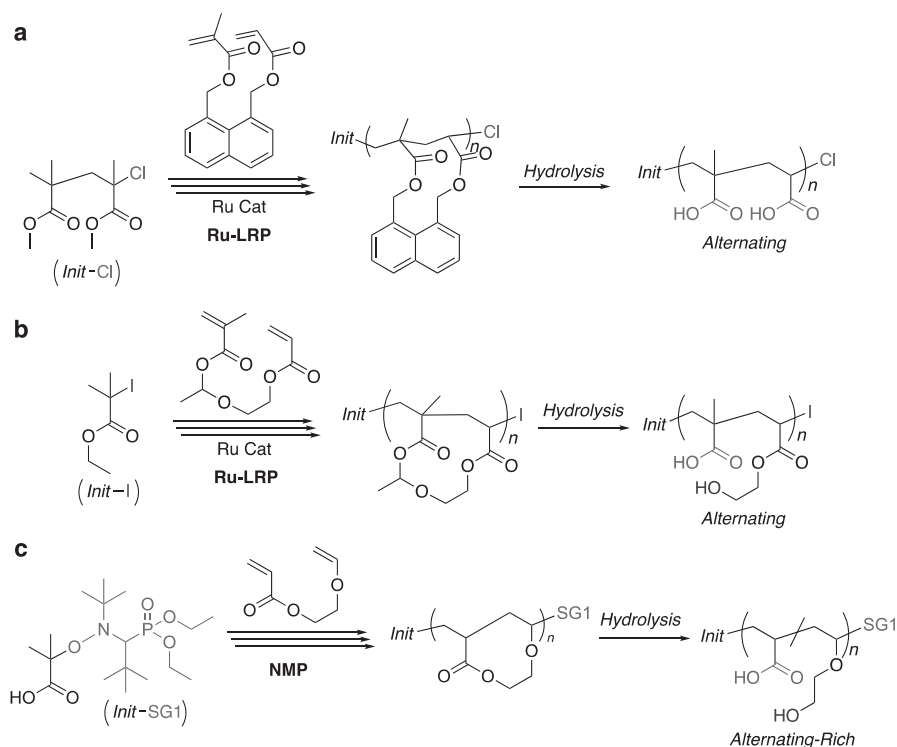


Figure 8 Alternating copolymers via selective cyclopolymerization and subsequent cleavage of the cyclo-spacer. A full color version of this figure is available at *Polymer Journal* online.

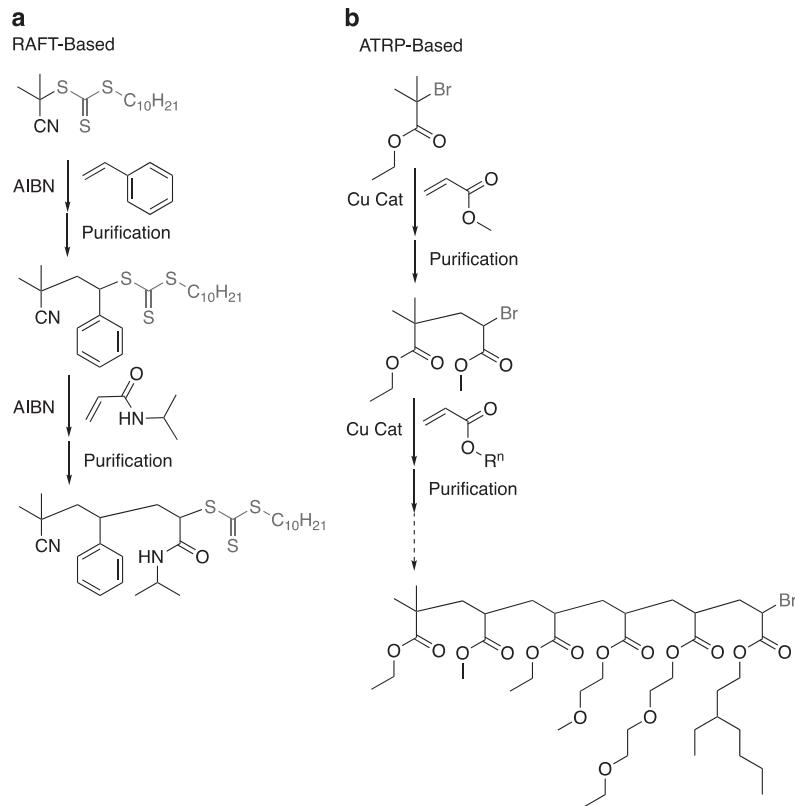


Figure 9 Iterative single unit addition (SUA) along with purification towards sequence-defined copolymers. A full color version of this figure is available at *Polymer Journal* online.

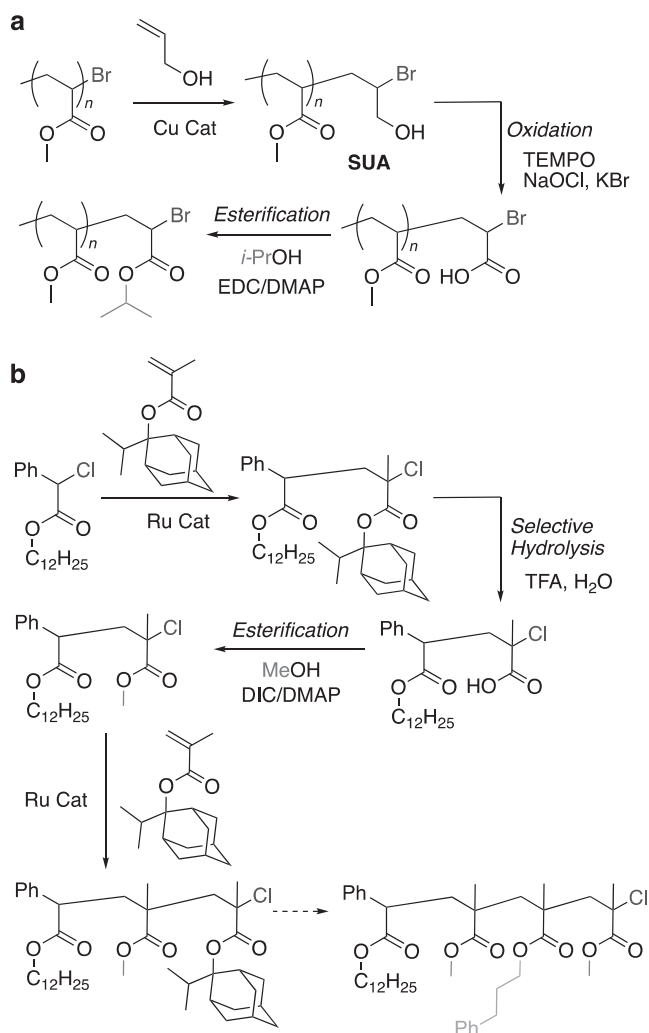


Figure 10 Sequence control via iterative radical addition along with pendant transformation. (a) Use of allyl alcohol with ATRP and (b) use of methacrylate carrying adamantyl and isopropyl groups with Ru-LRP. A full color version of this figure is available at *Polymer Journal* online.

polymerization to produce the terminal-defined copolymer; thus, the AAB sequence was directly and visually confirmed by MALDI-TOF-MS analysis.

ALTERNATING COPOLYMER VIA SELECTIVE CYCLOPOLYMERIZATION

Cyclopolymerization with a divinyl monomer has long attracted interest for the syntheses of unique topological polymers (i.e., cyclopolymers). The key to realize the cyclopropagation without crosslinking reactions is diluted conditions and/or a spacer design for making the double bonds relatively close to each other. Regarding sequence regulation, if a cleavable spacer is embedded between the two double bonds in the divinyl monomer, an alternating copolymer can be synthesized via cleavage of the resultant cyclo-pendant.

The concept was first realized with a methacrylate-acrylate divinyl monomer in which the double bonds were connected at the *peri*-position on a naphthalene scaffold (Figure 8a).⁵³ The monomer was polymerized with Ru-LRP under optimized diluted conditions to produce monodispersed polymers without forming an insoluble gel.

Importantly, the two vinyl groups were consumed at the same rate despite clearly different reactivities. The progress of cyclopolymerization was supported by the polymerization behaviors and by structural analyses using ¹H NMR spectroscopy and MALDI-TOF-MS. Given the innate reactivity ratios (i.e., $r_1 = 2.15$ and $r_2 = 0.40$, for MMA (M_1) and MA (M_2), respectively⁵⁴), the growing radical species (acrylate-based radical) can preferentially react with the more reactive methacrylate double bond. The resultant methacrylate radical undergoes intramolecular propagation with the acrylate double bond on the naphthalene unit beyond the inherent preference to the methacrylate monomer, which is due to the neighboring effect and the diluted conditions. Thus, the alternating propagation of the inter- and intra-reactions was repeated along with selectivity for the two double bonds. The resultant cyclopolymer was transformed into the alternating copolymer of methacrylic acid and acrylic acid via hydrolysis, and the acid copolymer was further transformed into the MMA and MA alternating copolymers via methylation with trimethylsilyl diazomethane.

An alternating sequence of different pendant groups was achieved by embedding a cleavable bond into different functional groups using a cyclopolymerization approach. Thus, a methacrylate double bond was connected to an acrylate via a hemiacetal ester bond that could then be cleaved into a carboxylic acid and a hydroxyl group via hydrolysis (Figure 8b).⁵⁵ The cyclopolymerization was also controlled with Ru-LRP under diluted conditions similar to those with the naphthalene-based monomer, and the cleavage allowed transformation into an alternating copolymer of methacrylic acid and 2-hydroxyethyl acrylate. Interestingly, the copolymer was soluble in 1,2-dimethoxyethane at lower temperature but became insoluble at higher temperature, whereas the random copolymer of the same compositional ratio (i.e., 1:1) and molecular weight was totally insoluble in the solvent regardless of temperature. The lower critical solution temperature-type phase behavior is interesting as a sequence-specific property.

Recently, the cyclopolymerization approach was expanded with a different monomer design in which two double bonds of acrylate and vinyl ether were simply connected via an ester bond (Figure 8c).⁵⁶ Nitroxide-mediated polymerization was suitable for the cyclopolymerization of the divinyl monomer, and the ester pendant was cleaved for transformation into the copolymer of acrylic acid and 2-hydroxyethyl vinyl ether. Although the accuracy of the alternating sequence was not high, it is interesting to synthesize an acrylate-vinyl ether copolymer with a high vinyl ether content (45%), which cannot be synthesized via general radical copolymerization.

SEQUENCE-DEFINED COPOLYMER VIA ITERATIVE SUA

Upon completion of the living polymerization with the first monomer, the sequential addition of a second monomer could produce a block copolymer if the dormant or active species is not irreversibly activated and is available for initiation of the second polymerization. As described above, the iterative monomer addition for highly controlled RDPD allows the construction of multiblock copolymers consisting of short segments with a variety of functional pendant groups. Even though one equivalent of monomer was sequentially added for repetition of a 'single unit addition (SUA)', it was impossible to synthesize a sequence-defined copolymer due to the statistical or distributed insertion of the added monomer based on the chain-growth mechanism.

If oligomerization can be suppressed to some extent for the addition reaction based on RDPD and if the single unit adduct is purified from the unreacted initiator, sequence-defined copolymers can be obtained.

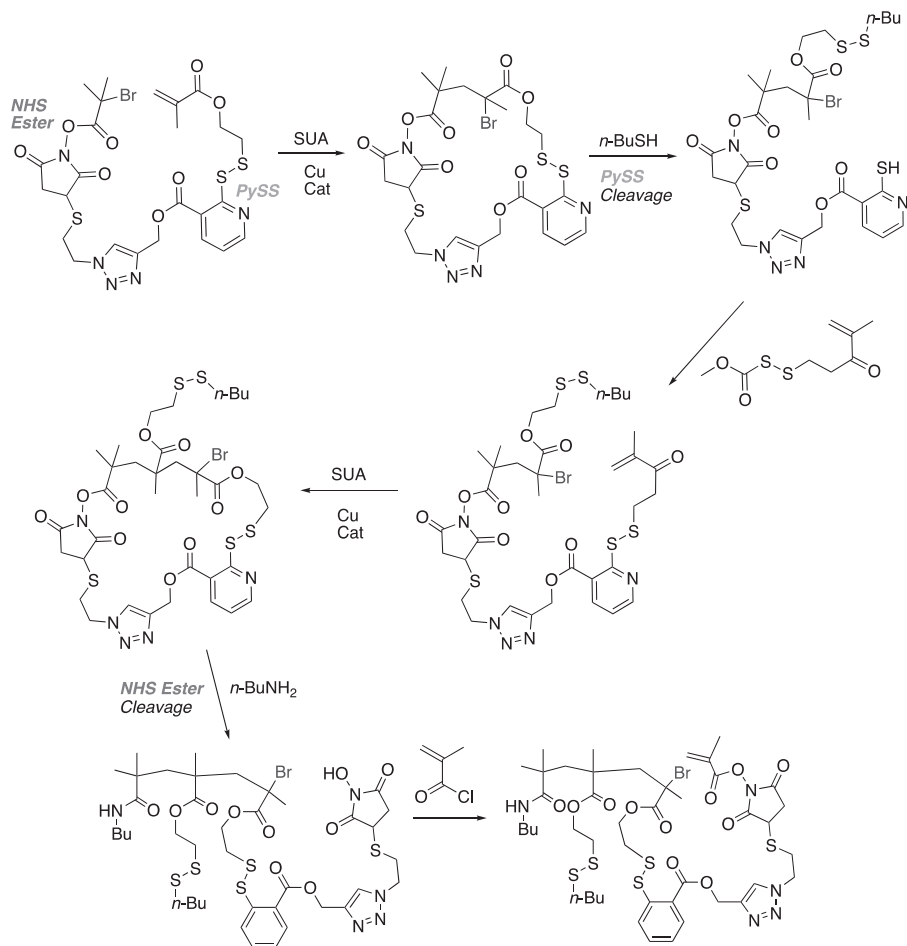


Figure 11 Sequence control via iterative cyclo-addition using the ATRP mechanism along with cleavage and renewing of the linker in the cyclic adduct. A full color version of this figure is available at *Polymer Journal* online.

For this approach, fast deactivation and/or kinetic control is required to facilitate the purification. Moad and co-workers⁵⁷ utilized the high transfer constant of cyanoisopropyl trithiocarbonate for RAFT and kinetic control to realize SUA with styrene (St), followed by a second SUA via the addition of *N*-isopropylacrylamide (Figure 9a).⁵⁷ Junkers and co-workers^{58,59} performed SUA with RAFT or photoinduced copper-mediated polymerization and isolated the single unit adduct from the distributed product with automated recycle size-exclusion chromatography. The iterative process along with SUA and the purification allowed the syntheses of sequence-defined oligomers while using the same type of monomer (e.g., acrylate); however, the total yield was decreased as the cycle was repeated (Figure 9b).

SUA can be controlled if the resultant dormant species is less reactive for radical generation than that of the starting dormant species, leading to suppression of chain-growth oligomerization. Indeed, some examples of atom transfer radical addition or the Kharasch addition reaction,⁶⁰ which is SUA on the basis of ATRP, rely on the mechanism of using non-conjugated olefins, producing less reactive dormant species in conjunction with more reactive halide compounds to produce conjugated radical species. To repeat the SUA process towards sequence control, some additional design or mechanism is required. Huang and co-workers⁶¹ proposed an idea for the iterative process along with transformation of an inert dormant species into an active species for the ATRP mechanism. Central to this approach is the use of allyl alcohol, whose pendant is a non-

conjugated methylene hydroxyl group that is suitable for SUA but can be converted into a conjugated carboxylic acid via oxidation and a further ester pendant via esterification (Figure 10a). The resultant carbon-halogen bond adjacent to the acrylate-based pendant ($-\text{COOR}$) is active for the next SUA, and repeating the cycle could lead to sequence control for acrylate units. However, the efficiency of the radical addition with allyl alcohol was not high, and repeated cycles were not achieved.

A monomer carrying a very bulky pendant group could show a low ability of homo-polymerization due to the steric hindrance or the low ceiling temperature. Such monomers may be suitable for the control of SUA with RDPD, and the transformation of the bulky pendant in the adduct into any less bulky substituent would allow an iterative process that leads to sequence-defined polymers (oligomers). A tertiary ester-based methacrylate carrying adamantyl and isopropyl groups exhibited little polymerization ability due to the bulkiness, and it underwent SUA for a chlorine-based initiator with Ru-LRP (Figure 10b).⁶² The selective acidic hydrolysis for the adamantyl pendant in the adduct followed by esterification with methanol produced the adduct of MMA. The resultant adduct was used as the initiator for the second SUA with the transformable bulky methacrylate, and the iterative process can lead to sequence-defined poly(oligo) methacrylate, unless an extremely bulky alcohol is used for the transformation. The three iterative cycles have been demonstrated to

give a sequence-defined oligomer consisting of three methacrylate units and an initiator.

Control of the selectivity in the competitive radical addition with two methacrylate monomers on the basis of Ru-LRP was demonstrated with halide initiators that carry a recognition site for one of the monomers via an ionic interaction⁶³ or a crown ether–cation interaction.⁶⁴ However, the concept is not appropriate for the iterative process for sequence regulation, unless some recognition sites for different comonomers are incorporated. The addition reaction is regarded as a cyclization and can be controlled via the reversible activation under diluted conditions while producing active halide dormant species. Thus, a new idea has been proposed to repeat the cyclization leading to sequence regulation: two types of cleaving and renewing covalent bonds were incorporated between the initiator for RDRP and the conjugated monomer (Figure 11).⁶⁵ Thus, an inimer (initiator–monomer) molecule was designed: the halide initiator for ATRP was connected with a methacrylate-based monomer via two orthogonally cleavable and renewable bonds, *N*-hydroxysuccinimide (NHS) ester and 2-disulfide pyridine. The addition of a primary amine allowed the cleavage of the former bond into amide and hydroxyl group of *N*-hydroxysuccinimide, followed by the reaction of acidic halide for regeneration of the *N*-hydroxysuccinimide ester. The addition of thiol led to cleavage of the latter bond into disulfide and 2-mercaptopyridine, followed by the reaction with activated disulfide for regeneration of 2-disulfide pyridine. Under the optimized conditions, due to ATRP, the cyclization almost quantitatively proceeded without oligomerization and irreversible side reactions (i.e., coupling and disproportionation) or cleavage of the embedded bonds. The subsequent cleavage of one of the bonds and regeneration along with incorporation of a methacrylic double bond were also quantitatively controlled; thus, two cycles were demonstrated to produce a sequence-defined trimer that included the initiator unit.

CONCLUSION

As shown above, the development of RDRP systems has certainly opened the door to sequence control for vinyl polymers. Controlled propagation without irreversible deactivation of the growing terminal is necessary to construct a carbon–carbon backbone, and an additional setup, such as a special molecular design (for the initiator, chain transfer agent, and monomer), switching of the stimulus for reversible activation and utilization of innate selectivity, allows control over the order of the pendant group, that is, ‘sequence’; however, the accuracy and variation are never equal to that of natural peptides. Some methodologies described in this review are still in the conceptual stage; however, expansion is expected towards a more useful process and more practical stages with material applications. In addition to methodologies to control the sequence of vinyl copolymers, developments of sequence analysis⁶⁶ of the obtained copolymers will become increasingly important. We expect further progress in sequence-controlled polymers.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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