J|A|C|S
COMMUNICATIONS

Concurrent Tandem Living Radical Polymerization: Gradient Copolymers via In Situ Monomer Transformation with Alcohols

Kazuhiro Nakatani, Takaya Terashima,* and Mitsuo Sawamoto*

Department of Polymer Chemistry, Graduate School of Engineering, Kyoto University,
Katsura, Nishikyo-ku, Kyoto 615-8510, Japan

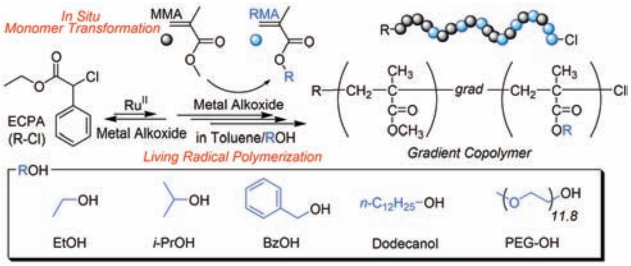
Received July 14, 2009; E-mail: terashima@living.polym.kyoto-u.ac.jp; sawamoto@star.polym.kyoto-u.ac.jp

An exquisite catalysis in polymer and materials chemistry implies an efficient, convenient, and versatile transformation from common reagents into functional designer materials. In terms of the efficiency and convenience, "tandem catalysis"[1] would be a candidate in which a simple one-pot synthetic approach involves multiple reactions concurrently or sequentially proceeding in a single reaction vessel without isolation of intermediates. Such methodologies have been extended to certain precision polymer syntheses coupled with hydrogenation,[2] racemization,[3] side chain functionalization,[4] and different polymerization systems.[5]

Transition metal-catalyzed living radical polymerization,[6] due to the high tolerance to polar functional groups including protic alcohols, now affords such functionalized polymers as end-functionalized,[7] star,[8] and gradient.[9] In these controlled radical processes, some additional cocatalysts[6,10] often play a vital role, in addition to initiators (organic halides) and metal complex catalysts. Among these cocatalysts are included metal alkoxides, which are quite effective not only in a ruthenium-mediated system[10] but also in transesterification of esters with alcohols.[11]

Intrigued by this particular aspect of metal alkoxides, we herein report a concurrent tandem living radical polymerization via in situ monomer transformation,[12] or a novel synthetic strategy for the synthesis of gradient copolymers (Scheme 1), whose efficiency, convenience, and versatility are clearly superior to those of the two conventional methods, one based on comonomer reactivity differences and the other on gradient feeding of comonomers.[9] The key is to employ a metal alkoxide [Al(O*i*-Pr)$_3$ or Ti(O*i*-Pr)$_4$][10] and an alcohol solvent (ROH) in the ruthenium-catalyzed living radical polymerization of unsaturated ester monomers such as methyl methacrylate (MMA) and methyl acrylate (MA). Combination of these metal alkoxides and alcohol solvents induces an in situ transesterification of the pendent esters just in the monomers and not in the polymers, concurrently with propagation, and thereby allows gradual changes in feed monomer composition and, in turn, in copolymer composition along the main chain. Note that, for this to be achieved, the propagation should be living or practically free from termination and chain transfer.

Scheme 1. Concurrent Tandem Living Radical Polymerization for Gradient Copolymers via In Situ Monomer Transformation of MMA



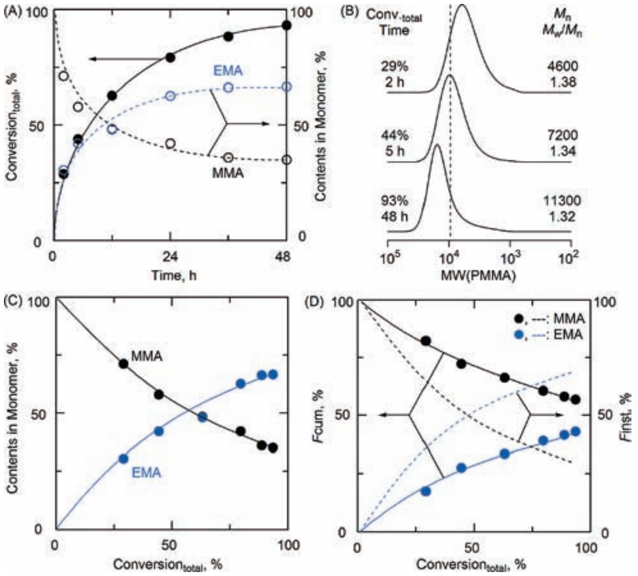


Figure 1. Concurrent tandem living radical copolymerization of MMA via in situ transesterification: (A) total conversion and monomer contents of MMA and EMA in polymerization solution and (B) SEC curves of products during the polymerization; (C) monomer contents in polymerization solution and (D) cumulative (F_{cum}) or instantaneous (F_{inst}) monomer contents in products as a function of total conversion; $[MMA]_0 = 2.0$ M; $[ECPA]_0 = 20$ mM; $[Ru(Ind)Cl(PPh_3)_2]_0 = 2.0$ mM; $[Al(Oi\text{-}Pr)_3]_0 = 20$ mM in toluene/EtOH (1/1, v/v: $[EtOH]_0 = 6.5$ M) at 80 °C.

Gradient Copolymers via In Situ Transesterification. First, transesterification of MMA was examined with Al(O*i*-Pr)$_3$ or Ti(O*i*-Pr)$_4$ in ethanol (EtOH)/tolunene (1/1, v/v) at 80 °C (Supporting Information: Figure S1A). Both metal alkoxides efficiently catalyzed the reaction to give ethyl methacrylate (EMA) in high yield (>80%), where the activity of Al(O*i*-Pr)$_3$ was lower than that of Ti(O*i*-Pr)$_4$ [50 h, conversion 75% (Al), 95% (Ti)].

To well synchronize the gradual compositional change in monomer and their copolymerization, Al(O*i*-Pr)$_3$ was employed as a cocatalyst for MMA; catalyst, [RuCl(Ind)(PPh$_3$)$_2$, Ind = η^5-C$_9$H$_7$];[7] initiator, ethyl 2-chloro-2-phenylacetate (ECPA)[2]; solvent, EtOH/toluene (1/1, v/v) at 80 °C. The polymerization smoothly proceeded to a high total monomer conversion, and the molecular weight distribution (MWD) of the obtained polymers, as measured by SEC, was narrow and shifted to higher molecular weight as the conversion increased (48 h: 93%, $M_n = 11\,300$, $M_w/M_n = 1.32$) (Figure 1A, 1B; Table S1). Direct ^{1}H NMR analysis of the polymerization mixtures actually revealed the gradual increase of EMA contents (Figure 1A: dash lines and 1C).

The cumulative EMA content ($F_{cum,\ EMA}$), obtained by ^{1}H NMR for each conversion, gradually increased from 0 to ca. 45%, while that of MMA ($F_{cum,\ MMA}$) in turn decreased (Figure 1D: blue solid

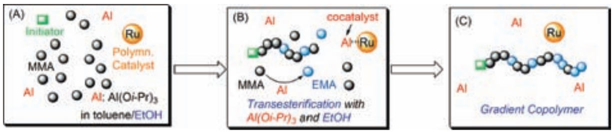
10.1021/ja9058348 CCC: $40.75

line; Figure S2). The instantaneous EMA content ($F_{\text{inst, EMA}}$, Figure 1D: blue dash line), calculated from the differential increase in *F*cum, EMA, also gradually increased with the total conversion from 0 to 68%, suggesting that gradient copolymers were obtained via a concurrent tandem living radical polymerization (Table S2, Figure S3).[9]

Mechanism. In the absence of A1(O*i*-Pr)$_3$, no pendent transesterification proceeded, and the polymerization was also retarded in the latter stage where the originally brown solution turned dark brown indicating some catalyst deactivation (Figure S4). These indicate a dual role of A1(O*i*-Pr)$_3$ as a transesterification catalyst in one part and a polymerization cocatalyst in the other. More importantly, the pendent group transformation proceeded specifically on MMA monomer and not on its polymers, as indicated by a separate observation that a poly(MMA) sample (M_n = 12 500, M_w/M_n = 1.14) was not transesterified with A1(O*i*-Pr)$_3$ in EtOH under similar conditions (Figure S5). In addition, the ruthenium-catalyzed random copolymerization of MMA and EMA gives almost the same monomer reactivity ratios (Figure S6). Thus, the instantaneous composition (MMA/EMA ratio) in products (F_{inst}) is in fact determined only by the corresponding in situ monomer composition (Figure 1C and 1D: dash lines).

Therefore, these results strongly support the proposed tandem catalysis (Scheme 2) where A1(O*i*-Pr)$_3$-catalyzed selective transesterification of MMA with EtOH gradually produces EMA during the polymerization and thereby continuously varies the monomer composion in the solution (A to B), finally giving well-controlled gradient copolymers of MMA and EMA (C). In addition, A1(O*i*-Pr)$_3$, after treatment with EtOH, completely turned into A1(OEt)$_3$, which would be a true cocatalyst in this tandem copolymerization (Figure S7).

Scheme 2. Proposed Mechanism of Concurrent Tandem Living Radical Polymerization for Gradient Copolymers via In Situ Transesterification of MMA



Versatility. We then applied various alcohols such as isopropanol (secondary), benzyl alcohol, 1-dodecanol (long alkyl), and poly(ethylene glycol) (PEG) methyl ether (polymeric), to the tandem copolymerization of MMA (Table 1, entries 2−5; Figures S8−12). Ti(O*i*-Pr)$_4$[10] was employed as a metal alkoxide to realize transesterification with various alcohols (Figure S1B). All these reactions efficiently produced well-controlled gradient copolymers derived from the corresponding alcohols (Table 1, Figure S14). This system can be further extended to methyl acrylate (MA) (entry 6, Figure S13), giving acrylic gradient copolymers.

Physical Properties. The gradient copolymers showed unique physical properties, differentiating them from the corresponding random and block counterparts. For example, the copolymers with 1-dodecanol exhibited a broad glass transition temperature (by differential scanning calorimetry) (Figure S15).[13] Additionally, the solubility of the PEG-bearing gradient copolymers in 2-propanol (3 wt %) was thermosensitive with an upper critical solution temperature (UCST: ca. 19 °C) clearly lower than that for the corresponding random copolymers (ca. 37 °C) (Figure S16).[8b]

In conclusion, we developed a novel concurrent tandem living radical polymerization, where metal-catalyzed copolymerization and metal alkoxide-catalyzed transestrification of a simple methyl (meth)acrylate with various alcohols were synchronized with propagation to produce controlled gradient copolymers, efficiently, conveniently, and in one pot. This methodology opened up new vistas to produce well-defined materials from simple and common alcohols.

Table 1. Various Gradient Copolymers via Concurrent Tandem Living Radical Polymerization[a]

entry	alcohol	time (h)	M_n[b]	M_w/M_n[b]	$F_{\text{cum,M(M)A}}/F_{\text{cum,R(M)A}}$[c]
1	EtOH	36	11 200	1.36	28/72
2	*i*-PrOH	33	11 900	1.37	55/45
3	BzOH	22	12 900	1.45	55/45
4	Dodecanol	22	20 700	1.21	56/44
5[d]	PEG-OH	10	28 000	1.17	69/31
6[e]	EtOH	72	7700	1.66	45/55

[a] $[\text{MMA}]_0$ = 2.0 M; $[\text{ECPA}]_0$ = 20 mM; $[\text{Ru(Ind)Cl(PPh}_3)_2]_0$ = 2.0 mM; $[\text{Ti(O}i\text{-Pr)}_4]_0$ = 20 mM in toluene/alcohol (1/1) at 80 °C; Conv. > 80%. [b] Measured by SEC. [c] Calculated from ^{1}H NMR. [d] $[\text{MMA}]_0$ = 0.5 M; $[\text{ECPA}]_0$ = 5.0 mM; $[\text{Ru(Ind)Cl(PPh}_3)_2]_0$ = 2.0 mM; $[\text{Ti(O}i\text{-Pr)}_4]_0$ = 20 mM in PEG-OH. [e] $[\text{MA}]_0$ = 2.0 M; [Ethyl 2-bromoisobutyrate]$_0$ = 20 mM; $[\text{Ru(Cp*)Cl(PPh}_3)_2]_0$ = 2.0 mM; $[\text{Al(O}i\text{-Pr)}_3]_0$ = 20 mM; $[n\text{-Bu}_3\text{N}]_0$ = 20 mM. Cp*: η^5-$C_5(CH_3)_5$.

Acknowledgment. K.N. expresses his thanks for JSPS Research Fellowships for Young Scientists. The authors also thank Dr. Makoto Ouchi in their laboratory for helpful comments.

Supporting Information Available: Experimental details and polymerization results including ^{1}H NMR spectra, GPC curves, DSC. This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) Wasilke, J.-C.; Obrey, S. J.; Baker, R. T.; Bazan, G. C. *Chem. Rev.* **2005**, *105*, 1001–1020. (b) Ajamian, A.; Gleason, J. L. *Angew. Chem., Int. Ed.* **2004**, *43*, 3754–3760.
(2) Terashima, T.; Ouchi, M.; Ando, T.; Sawamoto, M. *J. Am. Chem. Soc.* **2006**, *128*, 11014–11015.
(3) Van As, B. A. C.; van Buitenen, J.; Heise, A.; Broxterman, Q. B.; Verzijl, G. K. M.; Palmans, A. R. A.; Meijer, E. W. *J. Am. Chem. Soc.* **2005**, *127*, 9964–9965.
(4) (a) Geng, J.; Lindqvist, J.; Mantovani, G.; Haddleton, D. M. *Angew. Chem., Int. Ed.* **2008**, *47*, 4180–4183. (b) Popescu, D.; Keul, H.; Moeller, M. *Macromol. Chem. Phys.* **2009**, *210*, 123–139.
(5) (a) Mecerreyes, D.; Moineau, G.; Dubois, P.; Jérôme, R.; Hedrick, J. L.; Hawker, C. J.; Malmström, E. E.; Trollsas, M. *Angew. Chem., Int. Ed.* **1998**, *37*, 1274–1276. (b) Bielawski, C. W.; Louie, J.; Grubbs, R. H. *J. Am. Chem. Soc.* **2000**, *122*, 12872–12873.
(6) (a) Kamigaito, M.; Ando, T.; Sawamoto, M. *Chem. Rev.* **2001**, *101*, 3689–3745. (b) Kamigaito, M.; Ando, T.; Sawamoto, M. *Chem. Rec.* **2004**, *4*, 159–175. (c) Ouchi, M.; Terashima, T.; Sawamoto, M. *Acc. Chem. Res.* **2008**, *41*, 1120–1132. (d) Matyjaszewski, K.; Xia, J. *Chem. Rev.* **2001**, *101*, 2921–2990.
(7) (a) Coessens, V.; Pintauer, T.; Matyjaszewski, K. *Prog. Polym. Sci.* **2001**, *26*, 337–377. (b) Nakatani, K.; Ouchi, M.; Sawamoto, M. *Macromolecules* **2008**, *41*, 4579–4581.
(8) (a) Gao, H.; Matyjaszewski, K. *Prog. Polym. Sci.* **2009**, *34*, 317–350. (b) Terashima, T.; Ouchi, M.; Ando, T.; Kamigaito, M.; Sawamoto, M. *Macromolecules* **2007**, *40*, 3581–3588.
(9) (a) Matyjaszewski, K.; Ziegler, M. J.; Arehart, S. V.; Grenzta, D.; Pakula, T. *J. Phys. Org. Chem.* **2000**, *13*, 775–786. (b) Miura, Y.; Shibata, T.; Satoh, K.; Kamigaito, M.; Okamoto, Y. *J. Am. Chem. Soc.* **2006**, *128*, 16026–16027.
(10) Ando, T.; Kamigaito, M.; Sawamoto, M. *Macromolecules* **2000**, *33*, 6732–6737.
(11) Dubois, Ph.; Jacobs, R.; Jérôme, R.; Teyssié, Ph. *Macromolecules* **1991**, *24*, 2266–2270.
(12) Bories-Azeau, X.; Armes, S. P. *Macromolecules* **2002**, *35*, 10241–10243.
(13) Kim, J.; Mok, M. M.; Sandoval, R. W.; Woo, D. J.; Torkelson, J. M. *Macromolecules* **2006**, *39*, 6152–6160.

JA9058348