

SHORT COMMUNICATION

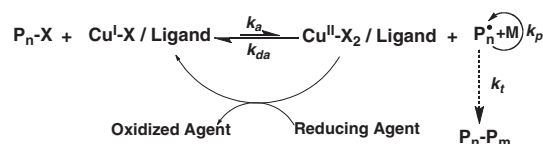
ARGET ATRP Synthesis of Thermally Responsive Polymers with Oligo(ethylene oxide) Units

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Atom transfer radical polymerization (ATRP) is one of the most efficient techniques for synthesis of polymers with precisely controlled molecular architecture,^{1–4} various hybrid materials,^{5–8} and bioconjugates.⁹ However, one limitation of ATRP is difficult removal of the catalyst complex from polar polymers. We have recently reported new initiating systems for ATRP, based on the activation of oxidatively stable Cu(II) complexes in the presence of various reducing reagents.^{10–14} The activator regenerated by electron transfer (ARGET) process uses a much lower concentration of catalyst and relies on a slow steady regeneration of Cu(I) from Cu(II) species that are continuously formed by unavoidable radical termination reactions (Scheme 1).^{12–14} Consequently, the amount of Cu(II) added to the reaction is much lower than the amount of reducing agent (just needed to balance the termination process). ARGET ATRP was successfully applied to grafting from various surfaces, such as silicon wafers, without deoxygenation.¹⁵ However, there is no report on the polymerization of the functional monomers using this method.

Thermoresponsive polymers exhibiting a lower critical solution temperature (LCST) in water have been increasingly investigated for nanotechnology and biotechnology applications.¹⁶ Polymers containing oligo(ethylene oxide) side chains, which are uncharged, water-soluble, non toxic thermoresponsive polymer, have been prepared by controlled polymerizations.^{17–22} We reported normal ATRP of di(ethylene glycol) methyl ether methacrylate (MEO₂MA), but control was limited due to the radical coupling, occurring above 50% conversion.²² The lower catalyst concentration should suppress the termination reactions, and moreover the simple procedure is very attractive for the polymerization of polar functional monomers such as MEO₂MA. We report here ARGET ATRP of MEO₂MA using ppm amounts of Cu and tin(II) 2-ethylhexanoate (Sn(EH)₂) as the reducing agent, providing a new strategy for the synthesis of smart materials such as stimuli-responsive polymers. The controlled polymerization proceeded well, even in the presence of a limited amount of air. Polymerization was carried out at 40 °C in anisole, in the presence of ethyl 2-bromoisobutyrate (EBiB) initiator and copper (II) bromide/tris[(2-pyridyl)methyl]amine (TPMA) complex as catalyst under deoxygenated conditions. The results are shown in Table I. In all entries, the apparent molecular weight of the polymer was slightly higher than theoretical, but the polymers had low polydispersity index (M_w/M_n). Monomer conversion, kinetic plots, and evolution of molecular weights with conversion are shown in Figure 1. Polymerization was started with 50 ppm of Cu and the reaction proceeded with first-order kinetics and a linear increase in molecular weight versus conversion. The molecular weights estimated by GPC increased linearly with conversion while retaining low PDI. Furthermore, the disappearance of a shoulder in the high molecular region in GPC traces indicated that the coupling was suppressed even at higher conversions (Figure S1 in Supporting Information). The polymerization conducted at 60 °C, reached conversion 80% after 4 h (entry 4). Entries 5 and 6 show the results under lower copper concentrations. The reaction proceeded even with 10 ppm of Cu to yield a polymer with high M_n relatively low M_w/M_n (entry 6).



Scheme 1. Proposed mechanism for ARGET ATRP.

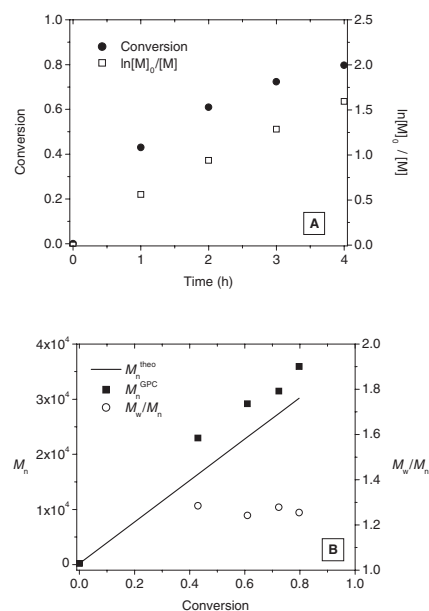


Figure 1. (A) First order kinetic plots, (B) Evolution of molecular weights for conversion for ARGET ATRP of MEO₂MA (Entry 3). Conditions: [MEO₂MA]₀/[EBiB]₀/[CuBr₂]₀/[TPMA]₀/[Sn(EH)₂]₀ = 200/1/0.01/0.05/0.1 in anisole 40 °C.

The polymerization was also carried out in the presence of limited amounts of air. In accordance with the previous report,¹⁵ the polymerization was carried out using a small-glass vial (22 mL size). A free space in the vial (~4 mL) should contain 0.0375 mmol of O₂ and can oxidize some Sn(EH)₂, [Sn(II)]_{air}. Therefore concentration of the effective Sn(II) is estimated from [Sn(II)]₀ – [Sn(II)]_{air}. Polymerization didn't occur when the molar ratio of the effective Sn(II) to EBiB, [Sn(II)]/[EBiB], was 0.25 (entry 7). The conversion stopped at 6% with 0.75 eq. of Sn(II) (entry 8). Polymerization started at the molar ratio [Sn(II)]/[EBiB] = 1.25 to yield PMEO₂MA with low M_w/M_n (entry 9). The reaction proceeded with first-order kinetics and a linear increase in molecular weight versus conversion (Figure S2 in

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Table I. Conversion and molecular weight data for ARGET ATRP of MEO₂MA^a

| Entry | Atmosphere | CuBr ₂ (ppm) | [Sn(EH) ₂]/[I] | [M]/[I] | Temp. (°C) | Time (h) | Conv. ^b | M _{n,theo} ^c | M _{n,GPC} ^d | M _w /M _n ^d |
|-------|----------------|-------------------------|----------------------------|---------|------------|----------|--------------------|----------------------------------|---------------------------------|---|
| 1 | N ₂ | 100 | 0.1 | 200 | 40 | 4 | 0.55 | 20,800 | 27,600 | 1.23 |
| 2 | N ₂ | 50 | 0.25 | 200 | 40 | 4 | 0.53 | 19,900 | 26,900 | 1.20 |
| 3 | N ₂ | 50 | 0.1 | 200 | 40 | 4 | 0.68 | 25,700 | 34,800 | 1.26 |
| 4 | N ₂ | 50 | 0.1 | 200 | 60 | 4 | 0.80 | 30,200 | 35,900 | 1.25 |
| 5 | N ₂ | 20 | 0.1 | 500 | 40 | 12 | 0.47 | 44,700 | 59,600 | 1.16 |
| 6 | N ₂ | 10 | 0.1 | 1000 | 40 | 15 | 0.53 | 99,800 | 114,000 | 1.27 |
| 7 | Air | 21 | 0.25 ^e | 480 | 40 | 6 | 0 | 0 | 0 | — |
| 8 | Air | 21 | 0.75 ^e | 480 | 40 | 6 | 0.06 | 5,400 | 7,500 | 1.25 |
| 9 | Air | 21 | 1.25 ^e | 480 | 40 | 12 | 0.53 | 49,000 | 41,200 | 1.22 |

^aConditions: [EBiB]₀/[CuBr₂]₀/[TPMA]₀ = 1/0.01/0.05 in anisole solution. [MEO₂MA]₀ = 2.67 M. ^bEstimated by GC. ^cCalculated from conversion. ^dDetermined by GPC in THF with PMMA calibration. ^eV(reaction solution) = 18 mL; V(free space) = 4 mL. [Sn(EH)₂] = ([Sn(EH)₂]₀ - [Sn(EH)₂]_{air}), where [Sn(EH)₂]_{air} = 2V(free space)(21%/22.4 L), 21% is the volume composition of O₂ in air, and 22.4 L is the volume of 1 mole of an ideal gas at STP.

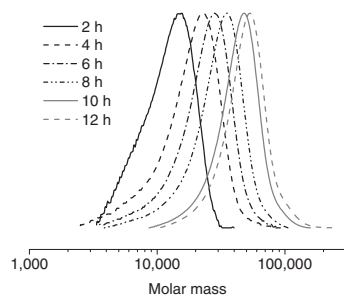


Figure 2. GPC traces for ARGET ATRP of MEO₂MA (Entry 9). Conditions: [MEO₂MA]₀/[EBiB]₀/[CuBr₂]₀/[TPMA]₀/[Sn(EH)₂]₀ = 480/1/0.01/0.05/2.0 in anisole 40 °C.

Supporting Information). Figure 2 illustrates GPC traces in entry 9 from Table I. The molecular weight of the polymer increased smoothly and the entire distribution shifted towards higher molecular weight.

Using UV-vis spectrometry, the light transmittance through a 0.3 wt % aqueous solution of PMEO₂MA was measured as the temperature increased (Figure S3 in Supporting Information). The polymer exhibited an LCST of 26 °C, which was consistent with the previous reports on PMEO₂MA prepared by living polymerizations (anionic and ATRP).^{18,19,22}

In conclusion, we demonstrated ARGET ATRP of MEO₂MA using tin(II) 2-ethylhexanoate as a reducing reagent. The polymerization was well controlled yielding a polymer with low M_w/M_n. A well controlled polymerization was achieved even in the presence of limited amounts of air which is a new method to prepare precisely controlled thermally responsive materials without rigorous purification procedures, such as deoxygenation, using small amount of Cu.

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Electronic Supporting Information Available: Figures S1, S2, and S3. These materials are available via the Internet at <http://www.spsj.or.jp/c5/pj/pj.html>.

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