Synthesis of Functional Polystyrenes by Atom Transfer Radical Polymerization Using Protected and Unprotected Carboxylic Acid Initiators

Xuan Zhang and Krzysztof Matyjaszewski*

Center for Macromolecular Engineering, Department of Chemistry, Carnegie Mellon University, 4400 Fifth Avenue, Pittsburgh, Pennsylvania 15213

Received April 12, 1999; Revised Manuscript Received September 8, 1999

ABSTRACT: Well-defined polystyrene (PSt) with terminal carboxylic acid groups can be prepared via atom transfer radical polymerization (ATRP). One method involves the use of protected α-halocarboxylic acid initiators. Unprotected α-halocarboxylic acid initiators, such as 2-bromobutyric acid (BBA), had low initiator efficiency of 0.1−0.2 and were not effective for the ATRP of styrene. Protection of the carboxylic acid group of BBA by a trimethylsilyl, *tert*-butyldimethylsilyl, or *tert*-butyl group led to improved initiator efficiencies of ca. 0.6, 0.8, and 1, respectively, for the ATRP of styrene. Subsequent hydrolysis of the protecting groups can afford well-defined PSt with terminal carboxylic acid groups. Another method involves the use of carboxylic acid initiators with remote halogens, such as 4-(1-bromoethyl)benzoic acid and 4-(2-(2-bromopropionyloxy)ethoxy)benzoic acid. Well-defined PSt with terminal carboxylic acid groups and low polydispersities were prepared with initiator efficiencies close to 0.7.

Introduction

Carboxylic acid-terminated polymers are of significant industrial interests due to their unique chemical and mechanical properties.[1,2] Carboxylic acid termini on polymers can be used to prepare various block copolymers, for example using the ring-opening polymerization of α,α-disubstituted β-propiolactones.[3] Carboxylic acid groups can also be easily transformed into other useful functional groups.[4,5] Traditionally, polymer chains with α,ω-functional carboxylic acid groups were prepared by controlled termination of living ionic polymerizations or by using functional initiators. However, due to the extreme sensitivity of living ionic polymerization to impurities and functional groups, these groups must be in a protected form. Multistep transformation or modification of polymerization conditions are often required to introduce functional groups. For example, carboxylation of poly(styryl)lithium is often complicated due to the formation of a significant amount of the corresponding dimer and trimer.[6−8] Protected carboxylic acid initiators, such as 4,4-dimethyl-2-oxazolin-2-ylmethyllithium, are not strong enough initiators for the anionic polymerization of styrene and methyl methacrylate and lead to low conversion of monomer and low initiator efficiency.[2]

Atom transfer radical polymerization (ATRP) is a method for controlled radical polymerization.[9,10] It is based on the reversible formation of carbon-centered radicals via homolytic cleavage of carbon−halogen bonds by transition metals in a low oxidation state, such as copper(I). The reversible deactivation of the radicals by halogen transfer from CuX_2/ligand to form dormant alkyl halides maintains a low concentration of the radicals while keeping the total concentration of propagating species constant. Recently, many advances have been made toward the polymerization of new monomers[11,12] and the development of new catalytic systems.[13−15] In particular, Xia and Matyjaszewski reported that the controlled polymerization of styrene, acrylates, and methacrylates has been achieved using multidentate aliphatic amines as the ligands.[13] ATRP has great tolerance to functional groups on the monomers and initiators.[9] Polymers with various α-functionality have been prepared using initiators containing hydroxyl, amino, allyl, vinyl, and epoxy groups.[16]

Previously, Haddleton et al. have reported the use of α-halocarboxylic acids as initiators for the ATRP of methyl methacrylate (MMA).[17] The initiator efficiency was quite low (0.3−0.4). In this paper, we report on the ATRP of styrene using two classes of carboxylic acid containing initiators. α-Halocarboxylic acids led to a controlled polymerization but with very low initiator efficiency (0.1−0.2). ATRP initiators with remote carboxylic acids afforded well-controlled polymerization with initiator efficiencies of 0.7. The difference in the initiator efficiency of the two classes of carboxylic acid-containing initiators is attributed to the formation of γ-butyrolactone in the case of α-halocarboxylic acids. Polymerization using trimethylsilyl-, *tert*-butyldimethylsilyl-, and *tert*-butyl-protected α-halocarboxylic acids is also discussed.

Experimental Section

Materials and Instrumentation. Styrene was distilled over CaH_2 and stored at −20 °C under argon prior to use. Copper(I) bromide was purified according to the literature procedure.[18] *N*,*N*′,*N*″,*N*‴-Pentamethyldiethylenetriamine (PMDETA), 4-(1-bromoethyl)benzoic acid, 2-bromobutyric acid, 2-bromoisobutyric acid, and *tert*-butyl 2-bromopropionate were all commercial products and were used without further purification. Monomer conversion was determined from the concentration of residual monomers on a Shimadzu GC-14 gas chromatograph equipped with a J&W Scientific 30 m DB0WAX column and a flame ionization detector with HE as the carrier gas. Molecular weights and molecular weight distributions were measured on PSS SDV columns (Guard, 10^5, 10^3, and 10^2 Å) coupled with a Waters 410 differential refractometer using THF as the eluent. ^{1}H NMR was performed on a Brucker WP300 instrument using $CDCl_3$ as the solvent.

Synthesis of 4-(2-Hydroxyethoxy)benzoic Acid. 4-(2-Hydroxyethoxy)benzoic acid was prepared by the reaction between 4-hydroxybenzoic acid and 2-chloroethanol according to the literature procedure.[19]

10.1021/ma990551d CCC: $18.00
Published on Web 09/30/1999

Synthesis of 4-(2-(2-Bromopropionyloxy)ethoxy)benzoic Acid. The compound was prepared by a modified literature procedure.[19] A dry 50 mL round-bottom flask with a stir bar was charged with (dimethylamino)pyridine (141 mg, 1.16 mmol), 4-(2-hydroxyethoxy)benzoic acid (1.77 g, 9.72 mmol), dry THF (20 mL), and dry triethylamine (3.37 mL, 24.2 mmol). The solution was cooled to 0 °C in an ice bath. 2-Bromopropionyl bromide (1 mL, 9.26 mmol) dissolved in dry THF (1.7 mL) was added dropwise slowly (ca. 10 min). A white precipitate was formed. After 1 h, the solution was allowed to warm to room temperature (rt) and was stirred for 12 h. The solid formed was filtered, and the solvent was removed under vacuum. To the yellow oil residue was added water (15 mL). A white precipitate (part of the crude product) appeared and was collected. The clear filtrate was acidified by addition of concentrated HCl to pH < 2. More white precipitate was formed and was collected. All the crude product was combined and recrystallized from acetone/water (2 mL/2 mL) to afford 0.8 g of product as a white powder. Physical data: mp = 146−147 °C. ^{1}H NMR (300 MHz, DMSO-d_6) δ: 12.6 (b, 1H, COO*H*), 7.9 (d, 2H, aryl), 7.0 (d, 2H, aryl), 4.7 (m, 1H, −C*H*(Br)CH$_3$), 4.5 (m, 2H, −PhOCH$_2$C*H*$_2$O−), 4.3 (m, 2H, −PhOC*H*2CH2O−), 1.7 ppm (d, 3H, −CH(Br)C*H*$_3$).

Synthesis of Trimethylsilyl 2-Bromobutyrate. A dry 50 mL round-bottom flask with a stir bar was charged with dry CH_2Cl_2 (80 mL), 2-bromobutyric acid (8.3 mL, 78 mmol), and dry triethylamine (10.8 mL, 77 mmol). The solution was cooled to 0 °C in an ice bath. Trimethylsilyl chloride (10.0 mL, 9.26 mmol, 79 mmol) was dissolved in dry CH_2Cl_2 (40 mL) and was added dropwise through a dropping funnel. A white precipitate was formed. The slurry was allowed to stir at rt for 1 h and then filtered through sintered glass. The solid was washed with CH_2Cl_2, and the filtrate was distilled to provide the product as a colorless liquid (70 °C at 10 mmHg). ^{1}H NMR ($CDCl_3$) δ: 4.14 (t, 1H, C*H*Br), 2.04 (m, 2H, C*H*$_2$CH$_3$), 1.06 (t, 3H, CH$_2$C*H*$_3$), 0.33 ppm (s, 9H, Si(C*H*$_3$)$_3$).

Synthesis of *tert*-Butyldimethylsilyl 2-Bromobutyrate. The compound was synthesized by the reaction between 2-bromobutyric acid and *tert*-butyldimethyl chloride using the above procedure. The product was isolated as a colorless oil. ^{1}H NMR ($CDCl_3$) δ: 4.18−4.10 (t, 1H, C*H*Br), 2.16−1.90 (m, 2H, C*H*$_2$CH$_3$), 1.12−0.98 (t, 3H, CH$_2$C*H*3), 0.33 ppm (s, 9H, Si(C*H*$_3$)$_3$).

Polymerization of Styrene. A dry round-bottom flask was charged with CuBr (39.1 mg, 0.27 mmol), PMDETA (56.3 μL, 0.27 mmol), styrene (3 mL, 26.2 mmol), anisole (0.5 mL, as GC standard), and a magnetic stir bar. The flask was sealed with a rubber septum and degassed by three freeze−pump−thaw cycles. The flask was immersed in an oil bath thermostated at 110 °C, and the initiator (0.27 mmol) was added dropwise. At timed intervals, aliquots of the reaction solution were withdrawn via syringes fitted with stainless steel needles and were dissolved in THF to measure conversion (GC) and molecular weight (SEC). The deprotection was carried out with HCl in boiling dioxane.

Results and Discussion

Effect of Added Carboxylic Acids. Styrene was polymerized in the presence of different amounts of benzoic acid to probe the effect of carboxylic acids on ATRP. The polymerization was carried out using CuBr complexed by *N*,*N*,*N*′,*N*″,*N*″-pentamethyldiethylenetriamine (PMDETA) as the catalyst in bulk at 110 °C and was initiated by the addition of 1-phenylethyl bromide. Initially, the solution was light green. Upon addition of the initiator, the polymerization solution quickly turned dark blue in contrast to the green color observed in the absence of benzoic acid. This observation is consistent with the literature data that carboxylic acids coordinate strongly with copper(II) and only weakly to copper(I) species.[18] The polymerization data are presented in Figures 1 and 2. The data indicate that the addition of 0.5 equiv of benzoic acid (relative to initiator) had no significant effect on the polymerization of styrene. Similar polymerization rate was observed with a linear increase of molecular weight with monomer conversion and low polydispersities. The addition of 1 equiv of benzoic acid led to a decrease in the polymerization rate without any effect on the control of the polymerization. The addition of 2 equiv of benzoic acid led to a further decrease in the polymerization rate and somewhat higher polydispersities. These results suggest that the carboxylic acid does not interfere with ATRP of styrene at low concentrations. However, side reactions with carboxylic acids, such as competition for the coordination of copper(II) and quaternization of amine ligands, may interfere with ATRP at high concentration of acids. These observations are consistent with the results reported by Percec et al.[20]

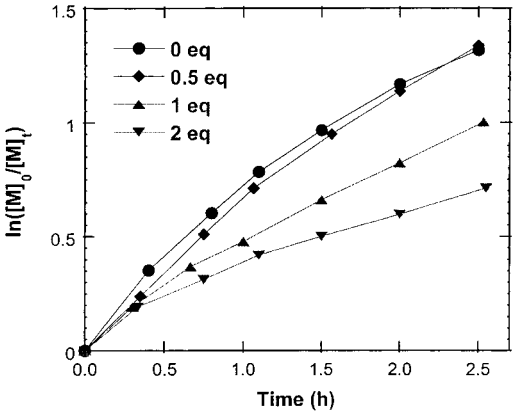


Figure 1. Semilogarithmic kinetic plot for the ATRP of styrene with added benzoic acid (0.5, 1, and 2 equiv to initiator). [CuBr]$_0$ = [1-phenylethyl bromide]$_0$ = [PMDETA]$_0$ = 0.078 M, [styrene]$_0$ = 7.5 M, and T = 110 °C.

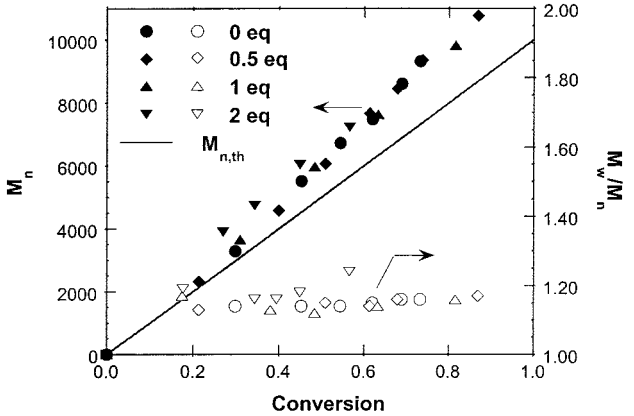


Figure 2. Evolution of experimental molecular weights and polydispersities with conversion for the ATRP of styrene with added benzoic acid (0.5, 1, and 2 equiv to initiator). [CuBr]$_0$ = [1-phenylethyl bromide]$_0$ = [PMDETA]$_0$ = 0.078 M, [styrene]$_0$ = 7.5 M, and T = 110 °C.

α-Halocarboxylic Acids as Initiators. The polymerization of bulk styrene was initiated by the dropwise addition of one of the α-halocarboxylic acids at 110 °C using CuBr/PMDETA as the catalyst (Figure 3). The polymerization solution turned dark blue instantly with the formation of a dark blue precipitate. The results shown in Table 1 indicate that various α-halocarboxylic acids can be used in ATRP to initiate polymerization. The resulting polymers had relatively narrow molecular weight distribution except those initiated by the primary α-halocarboxylic acid, 2-bromoacetic acid (entry 3).

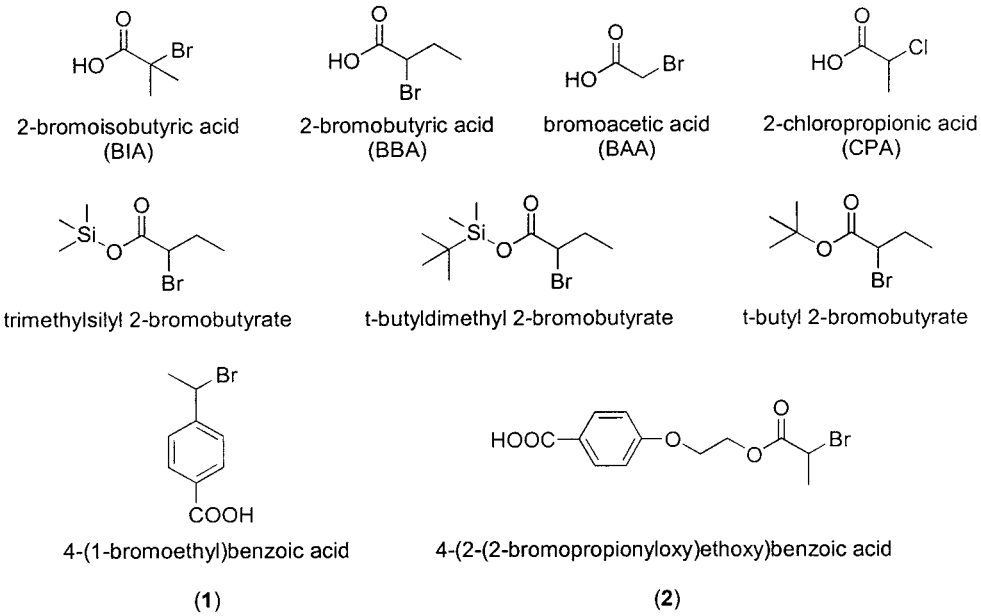


Figure 3. Structure of the initiators used in this paper.

Table 1. ATRP of Styrene Initiated by Unprotected α-Halocarboxylic Acids[a]

initiator[b]	time (h)	conv (%)	$M_{n,th}$	$M_{n,sec}$	M_w/M_n	I_{eff}
BIA	2.50	47.0	4700	47 000	1.34	0.10
BBA	2.00	49.0	4900	39 400	1.25	0.12
BAA	24.0	74.4	7440	237 100	1.75	0.03
CPA	24.0	97.7	9770	42 400	1.55	0.23

[a] Reaction conditions: $[CuBr]_0 = [PMDETA]_0 = [In]_0 = 0.09$ M in bulk styrene at 110 °C. [b] BIA = 2-bromoisobutyric acid, BBA = 2-bromobutyric acid, BAA = bromoacetic acid, CPA = 2-chloropropionic acid.

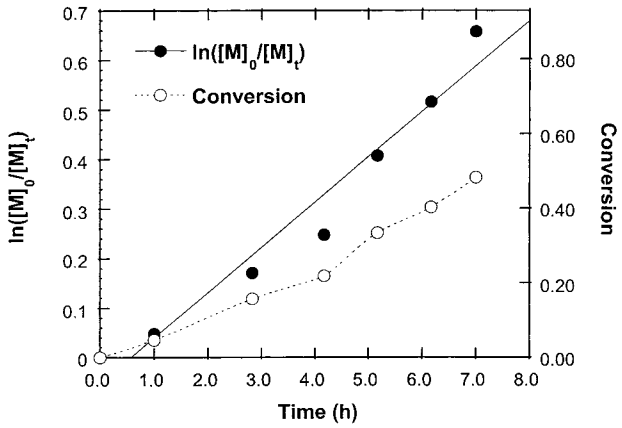


Figure 4. Semilogarithmic kinetic plot for the ATRP of styrene initiated by 2-bromobutyric acid (BBA). $[CuBr]_0 = [BBA]_0 = [PMDETA]_0 = 0.078$ M, $[styrene]_0 = 7.5$ M, and $T = 110$ °C.

However, the measured molecular weights, $M_{n,sec}$, were significantly higher than those calculated, $M_{n,th}$, indicating a low initiator efficiency. The polymerization using 2-bromobutyric acid as the initiator is shown as a representative example. The straight semilogarithmic plot of monomer conversion vs time (Figure 4) and the linear increase of molecular weight with conversion (Figure 5) suggested that there is no significant termination reactions present once the initiation step is complete. The low initiator efficiency ($I_{eff} = M_{n,th}/M_{n,sec}$) of α-halocarboxylic acids is attributed to an intramolecular cyclization reaction forming γ-butyrolactones

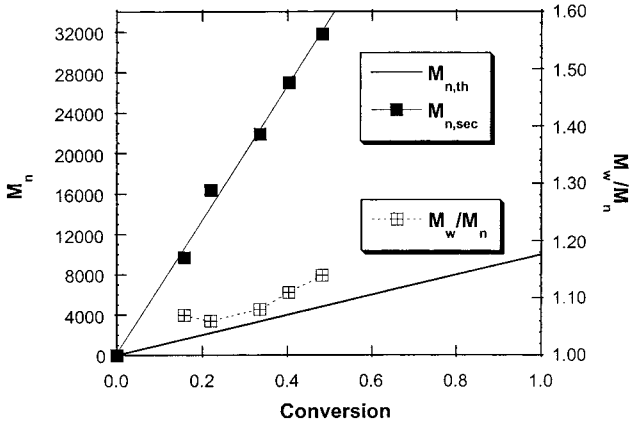
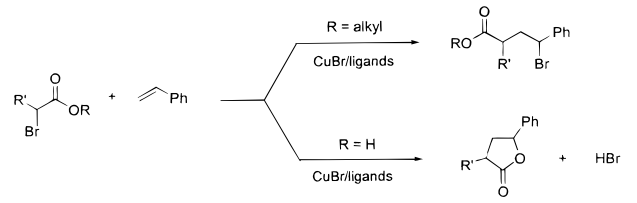


Figure 5. Evolution of experimental molecular weights and polydispersities with conversion for the ATRP of styrene initiated by 2-bromobutyric acid (BBA). $[CuBr]_0 = [BBA]_0 = [PMDETA]_0 = 0.078$ M, $[styrene]_0 = 7.5$ M, and $T = 110$ °C.

Scheme 1



(Scheme 1). This is consistent with literature reports that γ-butyrolactones can be prepared in high yields by the reaction between α-halocarboxylic acids and olefins under ATRA conditions.[21,22] Further evidence is provided by the results from the polymerization using initiator where the halogen is sufficiently distanced from the carboxylic acid group. High initiator efficiency was observed in these cases since intramolecular cyclization is not favored (vide infra). In addition, alkyl-protected α-halocarboxylic acids cannot form γ-butyrolactones under ATRA conditions, and indeed, alkyl-protected α-halocarboxylic acids lead to well-controlled polymerization with initiator efficiency close to unity (vide infra).

Alkyl-Protected α-Halocarboxylates as Initiators. Trialkylsilyl-protected 2-bromobutyric acids were

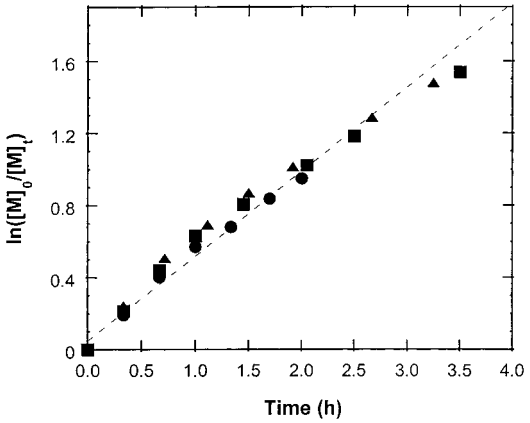


Figure 6. Semilogarithmic kinetic plot for the ATRP of styrene initiated by trimethylsilyl (●), *tert*-butyldimethylsilyl (■), and *tert*-butyl (▲) 2-bromobutyrate. $[CuBr]_0 = [initiator]_0 = [PMDETA]_0 = 0.078$ M, $[styrene]_0 = 7.5$ M, and $T = 110$ °C.

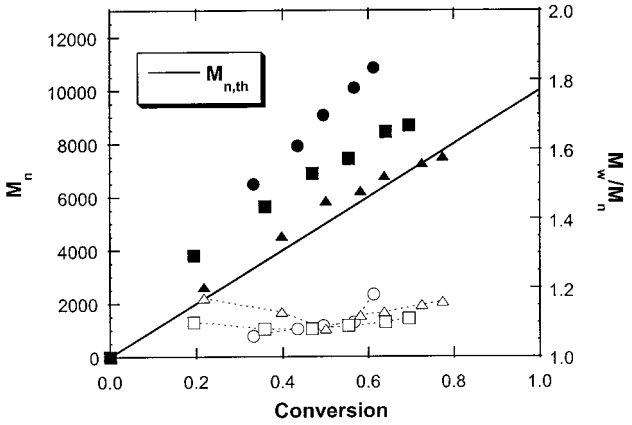


Figure 7. Evolution of experimental molecular weights and polydispersities with conversion for the ATRP of styrene initiated by trimethylsilyl (●, $M_{n,sec}$; ○, M_w/M_n), *tert*-butyldimethylsilyl (■, $M_{n,sec}$; □, M_w/M_n), and *tert*-butyl (▲, $M_{n,sec}$; △, M_w/M_n) 2-bromobutyrate. $[CuBr]_0 = [initiator]_0 = [PMDETA]_0 = 0.078$ M, $[styrene]_0 = 7.5$ M, and $T = 110$ °C.

prepared in an attempt to minimize cyclization reaction. For the trimethylsilyl-protected acid initiator, a linear semilogarithmic plot of conversion vs time was observed (Figure 6). The polymerization was well-controlled with molecular weights increasing linearly with conversion and polydispersities below 1.2 (Figure 7). The initiator efficiency was ca. 0.6. These observation indicate that the number of propagating chains remained constant and that the amount of termination reaction was negligible during the polymerization. The relatively low initiator efficiency suggested the presence of side reactions, such as hydrolysis of the trimethylsilyl-protecting group to afford the α-halocarboxylic acid and formation of γ-butyrolactone by the reaction directly between trimethylsilyl α-bromocarboxylate and styrene. Both reactions have been documented in the literature.[23,24] These side reactions in the early stages of the polymerization contributed to the inefficient initiation. By increasing the bulkiness of the protecting group to *tert*-butyldimethylsilyl, the proportion of both side reactions was reduced. The initiator efficiency was significantly improved (Figures 6 and 7). Hydrolysis of the silyl esters is likely due to a trace amount of moisture present in the polymerization medium. Exhaustive steps to exclude H_2O may improve the efficiency of these initiators.

When the carboxylic acid is protected by the *tert*-butyl ester, the hydrolysis of the protecting group and the

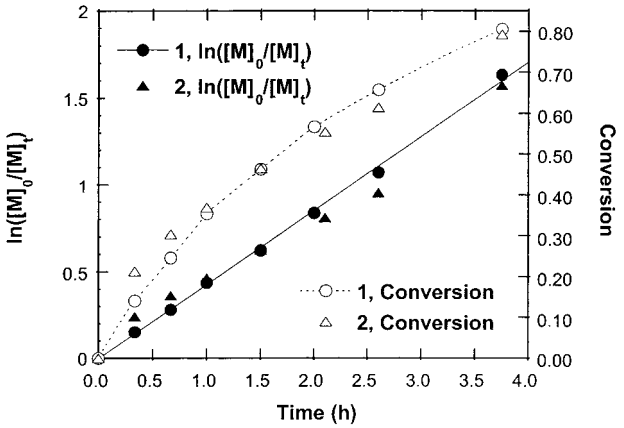


Figure 8. Semilogarithmic kinetic plot for the ATRP of styrene initiated by **1** or **2**. $[CuBr]_0 = [initiator]_0 = [PMDETA]_0 = 0.078$ M, $[styrene]_0 = 7.5$ M, and $T = 110$ °C.

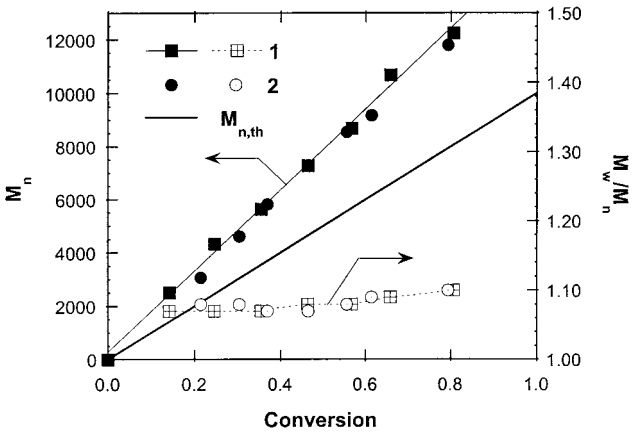


Figure 9. Evolution of experimental molecular weights and polydispersities with conversion for the ATRP of styrene initiated by **1** or **2**. $[CuBr]_0 = [initiator]_0 = [PMDETA]_0 = 0.078$ M, $[styrene]_0 = 7.5$ M, and $T = 110$ °C.

γ-butyrolactone formation are extremely slow under the polymerization conditions. The polymerization of styrene was well-controlled with initiator efficiency close to unity (Figures 6 and 7). Subsequent hydrolysis of trimethylsilyl, *tert*-butyldimethyl, and *tert*-butyl protecting groups will afford well-defined PSt with terminal carboxylic acid groups.[23]

Halo-Initiators with Remote Carboxylic Acid Groups. Carboxylic acids containing remote halogens, 4-(1-bromoethyl)benzoic acid (**1**) and 4-(2-(2-bromopropionyloxy)ethoxy)benzoic acid (**2**), were used as the initiators for the polymerization of styrene. The polymerization solution quickly turned dark blue upon addition of the initiators, suggesting the coordination of carboxylic acid groups to the transition-metal catalysts. The polymerization gradually turned viscous with time. Straight kinetic lines in the semilogarithmic plot of styrene conversion vs time were obtained for both initiators **1** and **2**, suggesting fast initiation and a constant number of propagating species (Figure 8). The $M_{n,sec}$ increased linearly with the conversion of styrene and was slightly higher than the theoretical molecular weight, $M_{n,th}$, assuming each initiator molecule initiated a polymer chain. The initiator efficiency ($I_{eff} = M_{n,th}/M_{n,sec}$) is ca. 0.7 for both initiator **1** and **2.** Additionally, the polydispersities of the polymers were low throughout the polymerization ($M_w/M_n \sim 1.1$, Figure 9). These results indicate that the presence of a carboxylic acid group remote to the initiation site does not interfere

with the polymerization of styrene. Well-defined PSt with terminal carboxylic acid groups can be prepared via ATRP using initiators with carboxylic acid groups remote to the initiating halogen.

Conclusions

Well-defined polystyrene with terminal carboxylic acid groups can be prepared via atom transfer radical polymerization. α-Halocarboxylic acids, such as 2-bromobutyric acid, had low initiator efficiency of 0.1−0.2 and were not effective for ATRP of styrene. The protection of 2-bromobutyric acid by trimethylsilyl, *tert*-butyldimethylsilyl, or *tert*-butyl led to an improved efficiency of ca. 0.6, 0.8, and 1, respectively, for the ATRP of styrene. Carboxylic acid initiators with remote halogens, such as 4-(1-bromoethyl)benzoic acid and 4-(2-(2-bromopropionyloxy)ethoxy)benzoic acid, yielded PSt with low polydispersities and with an initiator efficiency of 0.7.

Acknowledgment. Financial support by the industrial members of the ATRP Consortium at Carnegie Mellon University is gratefully acknowledged. We thank Dr. Scott G. Gaynor for helpful discussions.

References and Notes

(1) Kalfoglou, N. K.; Williams, H. L. *J. Appl. Polym. Sci.* **1973**, *17*, 1377.
(2) Broze, G.; Jérôme, R.; Teyssié, P. *Makromol. Chem.* **1978**, *197*, 1383.
(3) Sebenda, J. *J. Macromol. Sci., Chem.* **1972**, *6*, 1145.
(4) Perly, B.; Douy, A.; Galot, B. *Makromol. Chem.* **1976**, *177*, 2569.
(5) Allport, D. C. *Block Copolymers*; Allport, D. C., Janes, W. H., Eds.; Applied Science Publishers LTD: London, 1973; p 20.
(6) Wyman, D. P.; Allen, V. R.; Altares, J. T. *J. Polym. Sci., Part A* **1964**, *2*, 4545.
(7) Quirk, R. P.; Chen, W.-C. *Makromol. Chem.* **1982**, *183*, 2071.
(8) Quirk, R. P.; Yin, J. *Macromolecules* **1989**, *22*, 85.
(9) Matyjaszewski, K. *ACS Symp. Ser.* **1998**, *685*, 258.
(10) (a) Kato, M.; Kamigaito, M.; Sawamoto, M.; Higashimura, T. *Macromolecules* **1995**, *28*, 1721. (b) Wang, J. S.; Matyjaszewski, M. *J. Am. Chem. Soc.* **1995**, *117*, 5614. (c) Percec, V.; Barboiu, B. *Macromolecules* **1995**, *28*, 7970. (d) Haddleton, D. M.; Jasieczek, C. B.; Hannon, M. J.; Shooter, A. J. *Macromolecules* **1997**, *30*, 2190.
(11) Coca, S.; Jasieczek, C. B.; Beers, K. L.; Matyjaszewski, K. *J. Polym. Sci., Part A: Polym. Chem.* **1998**, *36*, 1417.
(12) Zhang, X.; Xia, J.; Matyjaszewski, K. *Macromolecules* **1998**, *31*, 5167.
(13) Xia, J.; Matyjaszewski, K. *Macromolecules* **1997**, *30*, 7697.
(14) Lecomte, P.; Drapier, I.; Dubois, P.; Teyssie, P.; Jerome, R. *Macromolecules* **1997**, *30*, 7631.
(15) Moineau, G.; Dubois, P.; Jerome, R.; Senninger, T.; Teyssie, P. *Macromolecules* **1998**, *31*, 545.
(16) (a) Matyjaszewski, K.; Coca, S.; Nakagawa, Y.; Xia, J. *J. Polym. Mater. Sci. Eng.* **1997**, *76*, 147. (b) Matyjaszewski, K.; Coessens, V.; Nakagawa, Y.; Xia, J.; Qiu, J.; Gaynor, S.; Coca, S.; Jasieczek, C. *ACS Symp. Ser.* **1998**, *704*, 16.
(17) Haddleton, D. M.; Heming, A. M.; Kukulj, D.; Duncalf, D. J.; Shooter, A. J. *Macromolecules* **1998**, *31*, 2016.
(18) Keller, R. N.; Wycoff, H. D. *Inorg. Synth.* **1946**, *2*, 1.
(19) Meng, X.; Natansohn, A.; Barrett, C.; Rochon, P. *Macromolecules* **1996**, *29*, 946.
(20) Sluis, M.; Barboiu, B.; Pesa, N.; Percec, V. *Macromolecules* **1998**, *31*, 9409.
(21) Matsumoto, H.; Nakano, T.; Ohkawa, K.; Nagai, Y. *Chem. Lett.* **1978,** 363.
(22) Phelps, J. C.; Bergbreiter, D. E.; Lee, G. M.; Villani, R.; Weinreb, S. M. *Tetrahedron Lett.* **1989**, *30*, 3915.
(23) Greene, T. W.; Wuts, P. G. M. *Protective Groups in Organic Synthesis*; John Wiley & Sons: New York, 1991.
(24) Matsumoto, K.; Ohkawa, K.; Ikemori, S.; Nakano, T.; Nagai, Y. *Chem. Lett.* **1979**, 1011.

MA990551D