Synthesis of Star Block Copolymers from Dendrimer Initiators by Combining Ring-Opening Polymerization and Atom Transfer Radical Polymerization

Youliang Zhao,[†] Xintao Shuai, Chuanfu Chen, and Fu Xi*

State Key Laboratory of Polymer Physics & Chemistry, Joint Laboratory of Polymer Science and Materials, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100080, China

Received August 18, 2004; Revised Manuscript Received September 7, 2004

ABSTRACT: Well-defined dendrimer-like star block copolymers up to 24 arm were successfully achieved by combination of living ring-opening polymerization (ROP) and atom transfer radical polymerization (ATRP) on the basis of poly(aryl ether) dendrimers (CMG*n*-OH, $n = 1-3$, with functionality of 6, 12, and 24, respectively). Star polylactides (CMG*n*-PLLA) were synthesized by bulk polymerization of L-lactide with multifunctional dendrimer initiators and stannous octoate catalyst. The molecular weights of CMG*n*-PLLA increased linearly with increasing monomer conversion, with molecular weight distributions remaining below 1.15, indicating the living nature of polymerization. CMG*n*-PLLA was converted into a macroinitiator CMG*n*-PLLABr via esterification with 2-bromoisobutyryl bromide. ATRP of methyl methacrylate (MMA) and styrene (St) using the CMG*n*-PLLABr/CuBr/pentamethyldiethylenetriamine initiating system afforded star block copolymers with predetermined molecular weights and narrow molecular weight distributions ($1.05 < M_w/M_n < 1.20$). The molecular weights of star polymers and star block copolymers could be adjusted by the variation of monomer-to-initiator ratios and monomer conversion. The precise arm numbers of 6, 12, and 24 for the resultant star polylactides and star block copolymers were confirmed by NMR spectra analysis and the hydrolysis approach, respectively.

Introduction

The construction of polymer materials with controlled compositions, topologies, and functionalities has been the enduring focus in current research.[1−4] Among them, star polymers have been extensively studied for a long time due to their branched structures and unique physicochemical properties different from those of their linear polymeric counterparts.[5−7] In general, there are roughly two strategies to generate star polymers: one is the so-called core-first method using multifunctional initiators;[8−13] another is the arm-first approach in which linear living polymer is synthesized initially, then following coupling reaction with a multifunctional coupling agent[4] or cross-linking reaction of linear living polymers using divinyl compounds.[14−20] So far, the core-first method has proven very efficient to form regular stars, and a series of well-defined star polymers with precise arm numbers up to 24 have been successfully synthesized by living radical polymerizations, especially atom transfer radical polymerization (ATRP).[21−29] More recently, the combination of various living polymerization techniques such as ATRP and ring-opening polymerization (ROP) to prepare novel star polymers[30−33] and star block copolymers[34−39] has attracted much attention since these combinatorial approaches can not only enrich the types of polymerizable monomers but also enable variable compositions, architectures, and properties into one polymeric structure.

Meanwhile, polylactide (PLA) and its copolymers are an important class of environmentally friendly biomaterials.[40−42] Until now, although poly(L-lactide) (PLLA) has been widely applied as bioresorbabale devices in drug delivery and tissue engineering, it has suffered from the lack of controlled degradation based on its high crystallinity and the induction of material defects based on lability of melt viscosity, so it is necessary to modify its physical properties.[40−44] In the past few years, some approaches such as introducing branched structures and hydrophilic units have been used to improve the biodegradability and hydrophilicity of PLLA, and many branched macromolecular architectures such as comb,[43,44] star,[45−52] and graft polymers[53−55] containing polylactide chains have been synthesized from viewpoints of synthesis and application. Among them, star polylactides are usually synthesized by ROP of lactide initiated by multifunctional initiators with terminal hydroxyl,[46−50] amine, and amide groups.[45,51]

For ROP of lactide using multifunctional initiators with high functionality (e.g., 8), the phenomenon of incomplete initiation[48−51] was always observed although dendrimer-like star polylactides up to 24 arms have been successfully synthesized by Hedrick's group recently.[56] For instance, when starburst PAMAM-OH dendrimers up to generation 4 (G*n*-OH, $n = 1-4$, with functionality of 8, 16, 32, and 64, respectively) were used as macroinitiators, the initiation efficiency significantly decreased with an increase in generation of dendrimer initiators.[50] In effect, the synthesis of regular star polymers is relative to some factors such as steric hindrance, initiation conditions,[13,57] and the nature of initiators.[50,58] In some cases, the backfolding of the dendrimer periphery may occur,[58] which can also lead to low initiation efficiency.

To evaluate the possibility of all terminal hydroxyl groups on the surface of dendrimer initiators starting growth of polylactide, poly(aryl ether) dendrimers with 1,3,5-tri(4-hydroxyphenoxy)benzene core, poly(benzyl

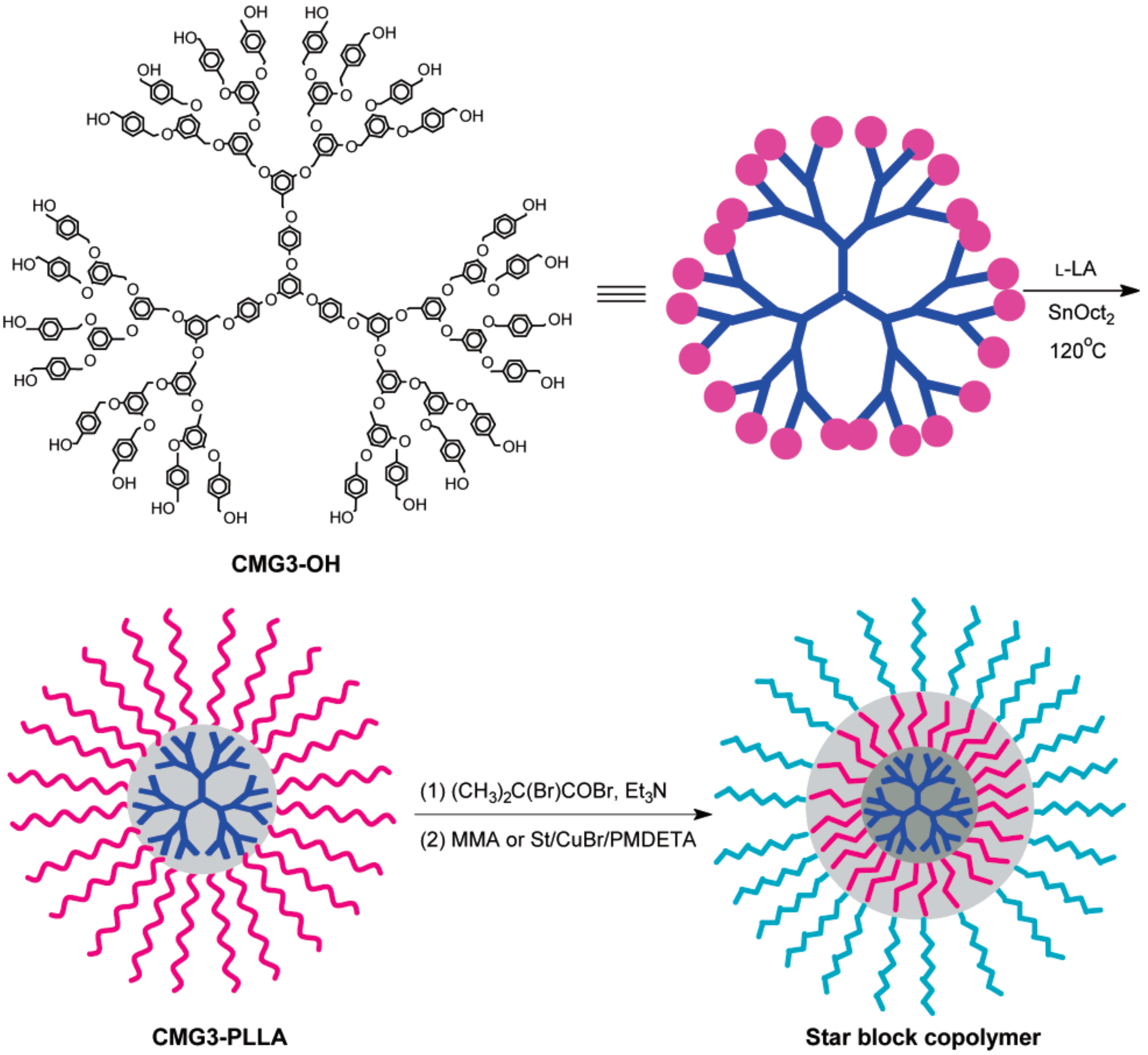
---

[†] Present address: Polymeric and Organic Materials Department, Graduate School of Science and Technology, Tokyo Institute of Technology, 2-12-1, Ohokayama, Meguro-ku, Tokyo 152-8552, Japan.

[*] Corresponding author: Tel +86-10-6255 7907; Fax +86-10-62559373; e-mail xifu@iccas.ac.cn.

10.1021/ma048303r CCC: \$27.50

Scheme 1. Synthesis of Star Block Copolymers by Mechanism Transformation



ether) interior, and benzyl alcohol surface group (CMG*n*-OH, $n = 1-3$, with functionality of 6, 12, and 24, respectively) were synthesized by our group recently.[29,39] The preliminary study indicated that these dendrimers could be used as efficient initiators for ROP of L-lactide.[39] Moreover, novel 24-armed star block copolymers with a dendrimer core such as star PLLA−PMMA and PLLA−PSt copolymers were successfully achieved by mechanism transformation (Scheme 1).[39] This article aims at reporting on the detailed synthesis of the above polymers, with a special emphasis on the effects of reaction conditions on successful synthesis of well-defined star polymers and star block copolymers.

Experimental Section

Materials. The dendrimer initiators (generations 1−3) were synthesized according to the literature procedure.[29,59] L-Lactide (Aldrich) was purified by recrystallization from toluene twice and dried in a vacuum at room temperature. Stannous octoate (Sigma) was distilled under reduced pressure before use. Toluene and tetrahydrofuran (THF) were distilled from metallic sodium and benzophenone. Styrene (St), methyl methacrylate (MMA), and pentamethyldiethylenetriamine (PMDETA) were stirred overnight over CaH_2 and distilled under reduced pressure prior to use. Triethylamine (TEA) was distilled over *p*-toluenesulfonyl chloride. Methylene chloride was dried over CaH_2 and distilled before use. CuBr was purified by stirring in acetic acid and washing with ethanol and then dried in vacuo. All the other reagents were of analytical grade and used as received.

Synthesis of Star Polylactides with a Dendrimer Core. The solution of CMG*n*-OH dendrimer ($n = 1-3$) in absolute THF was accurately weighed, placed into a dried glass tube, and then evaporated under vacuum at 50 °C for 8 h to remove residual solvent and water completely. After L-Lactide and stannous octoate were added, the tube was purged thrice with dry nitrogen and sealed under vacuum. The bulk polymerization was carried out at 120 °C in an oil bath with stirring. After reaction, the crude product was dissolved in chloroform, microfiltered through a 0.45 μm pore membrane filter, and precipitated into cold methanol twice. The polymer CMG*n*-PLLA was obtained as white fine powders.

CMG3-PLLA: FTIR (KBr): 3200−3600, 2998, 2947, 1759, 1615, 1502, 1456, 1386, 1365, 1268, 1215, 1186, 1133, 1089, 1045, 869, 757, 691 cm^{-1}. ^1H NMR ($CDCl_3$): δ 7.38 and 7.35 (ABq, *J* 8, Ph*H*), 6.90 and 6.87 (ABq, *J* 9, Ph*H*), 6.67 (s, Ar*H*), 6.55 (s, Ar*H*), 6.20 (s, Ar*H*), 5.17 (m, C*H* in PLLA), 5.01 (s, $PhCH_2O$), 4.97 (s, $ArCH_2O$), 4.35 (m, terminal C*H* in PLLA), 2.64 (d, terminal O*H* in PLLA), 1.59 (d, *J* 7, CH_3 in PLLA). ^{13}C NMR ($CDCl_3$): 175.0 (terminal $OCOCH(CH_3)OH$), 169.6 (*C*O PLLA), 160.0 (Ar*C*), 141.0 (Ar*C*), 135.8 (PhC-CH_2OPLLA), 134.0 (Ar*C*), 128.5 (Ph*C*), 127.8 (Ph*C*), 121.4 (Ph*C*), 114.2 (Ph*C*), 106.6 (Ar*C*), 101.4 (Ar*C*), 70.1 (Ar*C*H$_2$O), 69.6 (Ar*C*H$_2$O), 69.0 (*C*H in PLLA), 66.7 (terminal *C*H(CH$_3$)OH), 66.0 (Ph*C*H$_2$-OPLLA), 20.5 (terminal CH(*C*H$_3$)OH), 16.6 (*C*H$_3$ in PLLA).

Synthesis of CMG*n*-PLLABr Macroinitiator. The star PLLA samples were converted into ATRP initiators via esterification with 2-bromoisobutyryl bromide. A typical example is given below. CMG3-PLLA (9.80 g, 0.23 mmol) was dissolved in dry methylene chloride (100 mL) under stirring; to this solution was added triethylamine (1.12 mL, 8.0 mmol) under N$_2$. The mixture was stirred and cooled to 0 °C, and then 2-bromoisobutyryl bromide (0.99 mL, 8.0 mmol) in methylene chloride (10 mL) was added dropwise via a funnel over 30 min. The reaction mixture was stirred 30 h at room temperature before it was washed with solution of NaHCO$_3$ and water. The combined organic layer was dried overnight and concentrated, and the product CMG3-PLLABr was isolated from cold methanol. $M_{n,GPC} = 27.5$ kg/mol, $M_w/M_n = 1.08$, $DP_{NMR} = 21.6$.

CMG3-PLLABr: FTIR (KBr): 2997, 2947, 1758, 1616, 1502, 1455, 1384, 1363, 1268, 1186, 1132, 1092, 1047, 869, 757, 701 cm^{-1}. ^{1}H NMR (CDCl$_3$): δ 7.40 and 7.35 (ABq, *J* 8, Ph*H*), 6.96 and 6.93 (ABq, *J* 9, Ph*H*), 6.68 (s, Ar*H*), 6.55 (s, Ar*H*), 6.19 (s, Ar*H*), 5.17 (m, C*H* in PLLA), 5.03 (s, PhC*H*$_2$O), 4.96 (s, ArC*H*$_2$O), 1.98 (s, C(Br)(C*H*$_3$)$_2$)), 1.58 (d, *J* 7, C*H*$_3$ in PLLA).

The other macroinitiators were obtained according to the similar procedure. CMG1-PLLABr: $M_{n,GPC} = 43.5$ kg/mol, $M_w/M_n = 1.12$, $DP_{NMR} = 60.4$. CMG2-PLLABr: $M_{n,GPC} = 54.0$ kg/mol, $M_w/M_n = 1.14$, $DP_{NMR} = 58.2$.

Block Copolymerization with CMG*n*-PLLABr. CMG*n*-PLLABr was used as macroinitiator to prepare star block copolymers CMG*n*-PLLA-*b*-PMMA and CMG*n*-PLLA-*b*-PSt via ATRP with the CuBr/PMDETA catalytic system in bulk or solution. In a general procedure, a dry Schlenk flask with a magnetic stirrer was charged with CMG3-PLLABr macroinitiator (1.950 g, $M_{n,NMR} = 46.8$ kg/mol, $M_w/M_n = 1.08$, containing 1.00 mmol of C−Br group), CuBr (144 mg, 1.00 mmol), MMA (10.7 mL, 100 mmol), and anisole (37.0 mL). The reaction mixture was degassed with three freeze−evacuate−thaw cycles, and then deoxygenated PMDETA (210 μL, 1.00 mmol) was introduced into the flask by syringe under a nitrogen atmosphere. The flask was immersed into an oil bath thermostated at 80 °C. At timed intervals, about 2.0 mL of solution was withdrawn from the flask. The crude product was dissolved in chloroform, passed through a basic alumina column, and precipitated from a large amount of methanol. The polymerization conducted for 6 h afforded the copolymer CMG3-PLLA-*b*-PMMA in 52.8% conversion. $M_{n,GPC} = 112$ kg/mol, $M_w/M_n = 1.05$, $M_{n,NMR} = 173$ kg/mol.

CMG3-PLLA-*b*-PMMA: FTIR (KBr): 2997, 2951, 1761, 1733, 1615, 1483, 1453, 1385, 1363, 1271, 1242, 1187, 1148, 1091, 1048, 989, 844, 753, 697 cm^{-1}. ^{1}H NMR (CDCl$_3$): δ 7.40 and 7.34 (ABq, *J* 8, Ph*H*), 6.95 and 6.93 (ABq, *J* 9, Ph*H*), 6.68 (s, Ar*H*), 6.55 (s, Ar*H*), 6.19 (s, Ar*H*), 5.17 (m, C*H* in PLLA), 5.02 (s, PhC*H*$_2$O), 4.96 (s, ArC*H*$_2$O), 3.74 (s, terminal COOC*H*$_3$), 3.60 (s, COOC*H*$_3$ in PMMA), 2.62 (s, C*H*$_2$ in terminal group), 1.36−2.20 (m, C*H*$_3$ in PLLA and C*H*$_2$ in PMMA), 0.7−1.3 (m, C*H*$_3$ in PMMA).

CMG3-PLLA-*b*-PSt: FTIR (KBr): 3060, 3026, 2999, 2924, 2850, 1759, 1602, 1494, 1452, 1382, 1362, 1302, 1267, 1185, 1131, 1091, 1047, 870, 756, 699 cm^{-1}. ^{1}H NMR (CDCl$_3$): δ 7.40 and 7.34 (ABq, *J* 8, Ph*H*), 6.2−7.2 (m, Ph*H* in PSt and Ar*H* in dendrimer core), 5.17 (m, C*H* in PLLA), 5.03 (s, PhC*H*$_2$O), 4.96 (s, ArC*H*$_2$O), 4.2−4.5 (m, terminal C*H*(Ph)Br), 1.0−2.5 (m, C*H*$_3$ in PLLA, C*H* and C*H*$_2$ in PSt).

Hydrolysis of CMG*n*-PLLA-*b*-PSt. A 0.50 g sample of star block copolymers was dissolved in 50 mL of THF (50 mL). To this solution were added ethanol (30 mL), water (3 mL), and KOH (2.0 g) under nitrogen, and then the mixture was refluxed for 48 h. The solution was concentrated under reduced pressure and neutralized with dilute HCl. The crude product was extracted with chloroform, dried, and precipitated from methanol. The isolated linear polystyrene was obtained as white fine powders.

Characterization. Fourier transform infrared spectroscopic (FTIR) analyses were performed on a Perkin-Elmer 2000 spectrometer. ^{1}H and ^{13}C NMR spectra were recorded on a BRUKER DPX (300 MHz for ^{1}H and 75 MHz for ^{13}C) spectrometer in CDCl$_3$ or THF-d$_8$ at room temperature. The molecular weight and molecular weight distribution were measured on a Waters 150-C gel permeation chromatograph equipped with Ultrastyragel columns (HT2, HT3, and HT4) at 35 °C. THF was used as eluent, and polystyrene standards were used as calibrations. The absolute weight-average molecular weights were determined by static light scattering measurements in chloroform at 25 °C. The instrument used was a DLS-700 light scattering photometer equipped with a RM-102 differential refractometer. Unpolarized light of wavelength 632.8 nm was used, and scattering intensities were measured at angles from 30° to 150°. Absolute molecular weights were obtained by extrapolation of the scattering data to zero concentration and angle, according to the Zimm technique. Differential scanning calorimetric analysis (DSC) was carried out on a Perkin-Elmer DSC7 series thermal analysis system with a heating rate of 10 °C/min under a nitrogen atmosphere, relative to indium standards. Glass transition temperatures (T_g) were determined from the second run.

Results and Discussion

Synthesis and Characterization of Star PLLAs. In our previous study, it was found that not all the hydroxyl groups started the growth of PLLA chain when starburst PAMAM-OH dendrimers were used as macroinitiators for ROP of L-LA.[49,50] This phenomenon was essentially stemmed from the change in the density and distribution of hydroxyl groups on dendrimer surfaces and steric hindrance of the attached polylactide chains. Additionally, the existence of amide groups in the interior of PAMAM-OH dendrimers may disturb the polymerization since amide were also shown to be able to initiate the lactide polymerization although their reactivity was much weaker than that of hydroxyl groups.[45,52] To evaluate the possibility to synthesize star PLLAs with predictable arm numbers initiating from multifunctional initiators, novel poly(aryl ether) dendrimers up to third generation with terminal hydroxyl groups were designed and synthesized.[29,39] ^{1}H NMR, FTIR, and elemental analysis demonstrated these dendrimers possessed the chemical structure of the objective compounds. In this study, ROP of L-lactide using dendrimer initiators and stannous octoate catalyst was investigated.[39] The molar ratio of monomer to hydroxyl group on the surface of dendrimers ($[LA]_0/[OH]_0$) varied from 30 to 80, and the optimal reaction temperature was determined to be 120 °C. At lower temperatures, the solubility of dendrimer initiator in the melt of monomers was insufficient, resulting in low initiation efficiency. At higher temperatures, the resultant polymers possessed increased molecular weight distribution possibly originated from transesterification and thermal degradation in the course of polymerization.[41,43]

When ROP of L-LA was conducted in bulk at 120 °C for 24 h, various star PLLAs abbreviated as CMG*n*-PLLAs were synthesized, and the results are summarized in Table 1. Regular star polylactides with predetermined molecular weight, narrow molecular weight distribution, and precise functionality could be achieved under suitable conditions. All the hydroxyl groups on the surface of dendrimers initiated the polymerization, evident from ^{1}H and ^{13}C NMR spectra.[39] Take CMG3-PLLA obtained at various conversions for instance, the signal corresponding to PhC*H*$_2$OH protons of the dendrimer initiator (4.50 ppm) completely disappeared in ^{1}H NMR spectra, while the signal intensity of PhC*H*$_2$O at 5.01 ppm was correspondingly enhanced.

Table 1. General Characterization of CMG*n*-PLLAs Synthesized by ROP of L-Lactide Using CMG*n*-OH Initiators[a]

initiator	F^b	R^c	C (%)	$M_{n,calc}{}^d$ (kg/mol)	$M_{n,NMR}$ (kg/mol)	$M_{n,GPC}{}^e$ (kg/mol)	$M_w/M_n{}^e$	$M_{w,calc}$ (kg/mol)	$M_{w,SLS}{}^f$ (kg/mol)	T_g (°C)^g	T_m (°C)^g	X_c (%)^g
CMG1-OH	6	30	95.0	26.1	27.6	42.7	1.12	29.2	30.5	57.2	148.8	36.0
CMG1-OH	6	50	92.4	41.4	43.3	66.6	1.09	45.1	47.2	57.8	153.5	47.2
CMG1-OH	6	80	88.8	62.8	62.5	93.6	1.10	69.1	69.0	59.6	158.3	52.4
CMG2-OH	12	30	96.4	52.9	53.3	52.8	1.15	60.8	62.4	55.6	145.7	32.4
CMG2-OH	12	50	94.8	84.8	80.6	84.3	1.08	91.6	88.7	57.5	149.6	41.7
CMG2-OH	12	80	90.0	127	120	124	1.06	135	133	58.4	155.1	47.4
CMG3-OH	24	30	97.3	107	103	62.4	1.11	118	118	54.6	143.8	27.5
CMG3-OH	24	50	90.5	162	154	88.7	1.10	178	176	56.8	148.4	36.8
CMG3-OH	24	80	84.3	239	231	124	1.06	253	248	58.0	152.8	39.2

[a] Reaction conditions: $[LA]_0/[SnOct_2]_0 = 500$, 24 h, in bulk at 120 °C, part of results have been reported in the literature (ref 39). [b] Functionality of dendrimer initiators. [c] Feed ratios of monomer to hydroxyl group on the surface of dendrimer initiators. [d] Calculated from $M_{n,calc} = 144.13 \times ([M]_0/[OH]_0) \times C\% \times F + M_{wdendrimer}$, where $C\%$ means the monomer conversion. [e] Estimated by GPC analysis with polystyrene standard. [f] Determined by light scattering in $CHCl_3$. [g] Determined by DSC.

Meanwhile, no signal at 64.4 ppm ($PhCH_2OH$) or 143.3 ppm ($PhC{-}CH_2OH$) was observed in ^{13}C NMR spectra, while new signals appeared at 66.0 ppm ($PhCH_2$-OPLLA) and 135.8 ppm ($PhC{-}CH_2OPLLA$). Both results demonstrated that all the hydroxyl groups had quantitatively initiated the polymerization, which is different from the results in ROP of L-LA initiated with PAMAM-OH dendrimers,[50] revealing the strong dependence of forming well-defined star PLLAs on the nature of multifunctional initiators. In addition, the above results also indicate that no backfolding of the surface hydroxyl groups and steric hindrance occurred in the course of polymerization, which can be attributed to the relatively large molecular size and rigidity of dendrimer initiators.

Although GPC analysis based on linear polystyrene standards is not a reliable approach to determining the accurate molecular weight of star polymers, it is meaningful in estimating the molecular weight distribution. As a comparison, the molecular weights of star PLLAs were measured by GPC, ^1H NMR, and SLS. In Table 1, the number-average molecular weight determined by ^1H NMR spectra ($M_{n,NMR}$) was obtained by combination of arm number and average chain length determined by comparison of the average signal intensity ratios of methine protons of PLLA (5.17 ppm) to terminal methine protons (4.35 ppm), and the absolute weight-average molecular weight ($M_{w,SLS}$) was measured by light scattering in chloroform. In all cases, $M_{n,NMR}$ are close to the theoretical M_n values calculated from feed ratio and monomer conversion, $M_{w,SLS}$ are in good agreement with the predicted M_w values calculated using M_w/M_n determined by GPC, and the molecular weight distributions determined by GPC are relatively narrow ($1.06 < M_w/M_n < 1.15$), indicating the living nature of polymerization.

For polymerization using CMG3-OH initiator, the dependence of M_n and M_w/M_n of CMG3-PLLA on molar ratio of monomer to initiator is shown in Figure 1. The molecular weight linearly increases with an increase in $[LA]_0/[OH]_0$, confirming the role of the hydroxyl groups on dendrimer surfaces as effective propagation centers. The above result also suggests that the molecular weight of star PLLAs could be manipulated by the variation of monomer-to-initiator ratios.

In addition, the molecular weight of star PLLAs can also be adjusted by controlling monomer conversion. For instance, when CMG3-OH was used as initiator, the polymerization results at various times are shown in Figure 2. CMG3-PLLAs obtained at various conversions exhibit molecular weight close to the expected one, revealing the high initiation activity of dendrimer initiators. The molecular weight linearly increases with monomer conversion, and molecular weight distributions are relatively low ($M_w/M_n < 1.10$). The GPC traces (Figure 3) are symmetrical and monomodal, indicating no mixture of star polymer and linear one was formed, and the side reactions such as transesterification and thermal degradation during polymerization could be neglected.

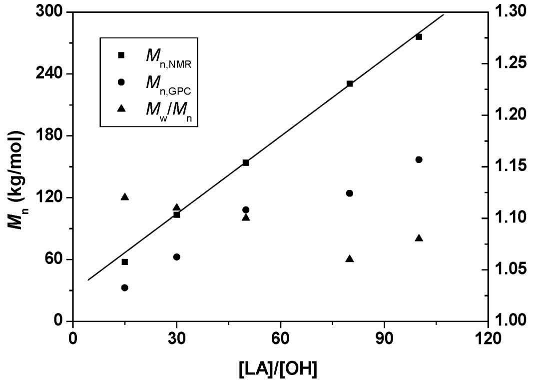


Figure 1. Dependence of M_n and M_w/M_n of CMG3-PLLA on $[LA]_0/[OH]_0$ for ROP of L-LA initiated with CMG3-OH. $[LA]_0/[SnOct_2]_0 = 500$, 120 °C, 24 h.

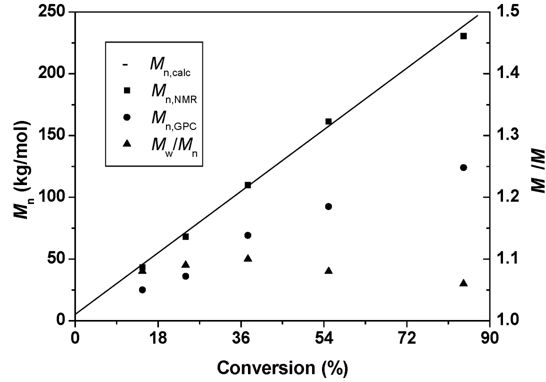


Figure 2. Polymerization results at various monomer conversions for ROP of L-LA using CMG3-OH initiator. $[LA]_0:[OH]_0:[SnOct_2]_0 = 80:1:0.16$, 120 °C.

DSC analysis was used to investigate the thermal properties of various star polylactides, and the results are listed in Table 1. As expected, the star PLLAs with various chain lengths and arm numbers showed the semicrystalline morphologies corresponding to isotactic structures. For various star PLLA samples with similar arm length, the glass transition temperatures (T_g), melting points (T_m), and degree of crystallinity (X_c, calculated by using the melting enthalpy of 93.6 J/g as

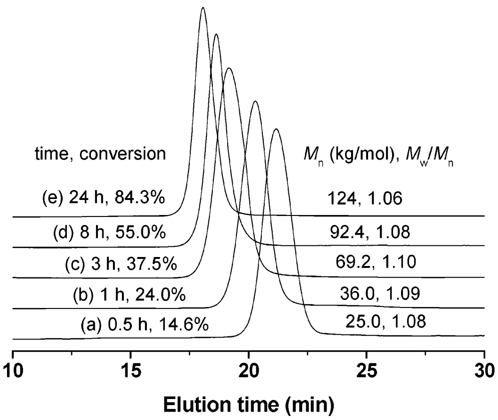


Figure 3. GPC traces of CMG3-PLLA obtained at various conversions. See Figure 2 for reaction conditions.

the perfectly crystalline PLLA[60]) are liable to decrease with an increase in branching degree of star polymers. The T_g values of various samples varied from 54.6 to 59.6 °C, which is similar to that of linear PLLA. The T_m values of star PLLAs containing dendrimer core were obtained in the range 140−160 °C, which is somewhat lower than that for linear high-molecular-weight PLLA. This phenomenon has also been observed by Choi,[46] Trollsås,[56] and our group[39,49,50] and can be attributed to the crystalline imperfections due to increased free end groups and branching points in the more branched polymers. Additionally, the crystallinity changes in a wide range from 27.5% to 52.4% and tends to decrease with an increase in branching degree, which can be attributed to the more restricted conformation of star PLLAs than linear PLLA.[46,50] It should be mentioned that the crystallinity of star PLLAs with dendrimer core synthesized in this study is apparently higher than that of dendritic PLLAs synthesized by Trollsås et al.[56] Based on the data of melting enthalpy, the crystallinity of dendritic PLLAs with 6, 12, and 24 end hydroxyl groups and targeted polymerization degree of 20 was estimated to be 32.4%, 24.3%, and 8.5%, respectively. The difference probably stemmed from the unique molecular architecture of dendritic polymers[61−63] and relatively low molecular weight between branching junctions.[56] As compared with regular star PLLAs with the same terminal hydroxyl groups, dendritic PLLAs are of more branching points and compact structures,[61−63] which will decrease the intermolecular interactions and restrict the macromolecular conformations, thus leading to more rigorous confinement of the crystallization behavior of polymers.[46]

Synthesis of ATRP Macroinitiator. When CMG*n*-PLLAs with various active hydroxyl chain ends were chosen as typical samples to react with 2-bromoisobutyryl bromide, CMG*n*-PLLABrs with slightly increased molecular weight and similar molecular weight distribution could be obtained. In ^{1}H NMR spectra (Figure 4), the signals at 4.35 ppm (terminal methine protons of CMG*n*-PLLA) and 2.64 ppm (terminal OH of CMG*n*-PLLA) wholly disappeared, while novel signal corresponding to methyl protons of 2-bromoisobutyrates appeared at 1.98 ppm, revealing that all the terminal hydroxyl groups have been quantitatively functionalized. Meanwhile, the broad absorption peak at 3200−3600 cm^{-1} corresponding to hydroxyl groups was absent from FTIR spectra of CMG*n*-PLLABr, also indicating the absence of hydroxyl groups in CMG*n*-PLLABr.

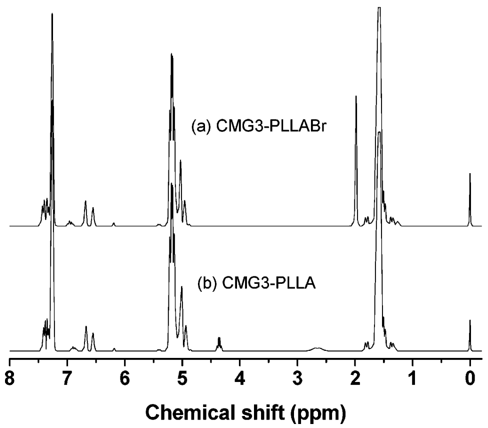


Figure 4. ^{1}H NMR spectra of CMG3-PLLABr (a) and CMG3-PLLA (b).

Synthesis of Star Block Copolymers by ATRP. Recently, increasing attention has been paid to synthesis of well-defined star polymers[30−33] and star block copolymers[34−39] by combination of ROP and ATRP. However, reports on synthesis of regular star block copolymers containing biodegradable polylactide blocks by this combinatorial technology were scarce; to the best of our knowledge, only Johnson et al. reported the synthesis of 6-armed star block copolymers with PLA blocks more recently.[37,38] In this study, to investigate the feasibility to synthesize regular 24-armed star block copolymers, ATRP of vinyl monomers such as MMA and St was performed with CMG*n*-PLLABr macroinitiator, and a series of novel star block copolymers such as CMG*n*-PLLA-*b*-PMMA and CMG*n*-PLLA-*b*-PSt with definite arm numbers up to 24 were achieved under appropriate conditions.

ATRP of MMA Using CMG*n*-PLLABr Macroinitiator. Although star PMMAs with arm number up to 24 have been synthesized by living radical polymerization initiated with multifunctional initiators,[27,34] the phenomenon of star−star coupling[24,25] was observed during polymerization when initiators with high functionality were used. For example, Angot et al. found that the star−star coupling existed in ATRP of MMA using calixarene-based multihalides with functionality up to 8.[10,24] In addition, Haddleton's group reported on the synthesis of 21-armed star PMMA via ATRP using a cyclodextrin-core-based initiator; however, a shoulder in the side of higher molecular weight was always observed in GPC traces even if the molecular weight distribution is rather narrow ($M_w/M_n \approx 1.05$).[25] To investigate whether well-defined star PLLA−PMMA block copolymers up to 24 arm can be achieved by ATRP, polymerization of MMA using the CuBr/PMDETA catalytic system was performed at 80 °C in bulk and anisole. From polymerization results as listed in Table 2, it can be seen that CMG*n*-PLLA-*b*-PMMAs with predetermined molecular weight and narrow molecular weight distribution ($1.06 < M_w/M_n < 1.15$) could be achieved by ATRP initiated with CMG*n*-PLLABr. For copolymers obtained at various conversions, the GPC traces exhibit monomodal and symmetrical distribution, indicating that the star−star coupling reaction during polymerization could be minimized under suitable conditions.

When polymerization of MMA using CMG3-PLLABr ($[M]_0$:$[I]_0$:$[CuBr]_0$:$[PMDETA]_0 = 100$:1:1:1, $[M]_0 = 2.0$ M) was carried out at 80 °C in anisole, the polymerization

Table 2. Results for ATRP of MMA with CMG*n*-PLLABr Initiator under Various Conditions[a]

						M_n (kg/mol)			
run	initiator	$[M]_0/[I]_0$	solvent	time (h)	C (%)	M_w/M_n[d]	$M_{n,calc}$[b]	$M_{n,NMR}$[c]	$M_{n,GPC}$[d]
1	CMG1-PLLABr	200	bulk	2	49.6	88.1	95.4	74.8	1.10
2	CMG1-PLLABr	200	anisole	2	25.4	59.0	62.5	49.6	1.15
3	CMG1-PLLABr	500	anisole	4	42.8	157	150	124	1.12
4	CMG2-PLLABr	200	bulk	2	48.1	171	155	108	1.12
5	CMG2-PLLABr	200	anisole	4	45.0	163	168	115	1.08
6	CMG2-PLLABr	400	anisole	6	47.5	283	256	172	1.11
7	CMG3-PLLABr	150	bulk	1	28.4	149	151	90.8	1.06
8	CMG3-PLLABr	100	anisole	4	39.2	141	139	87.5	1.09
9	CMG3-PLLABr	300	anisole	4	30.6	267	254	142	1.12

[a] Polymerization conditions: $[I]_0:[CuBr]_0:[PMDETA]_0 = 1:1:1$, at 80 °C, and $[M]_0 = 2.0$ M in solution polymerization, where $[I]_0$ stands for the concentration of all the initiation sites. [b] Calculated from $M_{n,calc} = 100.12 \times ([M]_0/[CMGn\text{-}PLLABr]_0) \times C\% + M_{winitiator}$. [c] Determined by ^{1}H NMR, the average chain length of PMMA was estimated by comparison of signal intensity ratios of methine protons of PLLA (5.17 ppm) to methyl protons of PMMA (3.60 ppm) based on the DP value of PLLA. [d] Estimated by GPC calibrated by PS standard.

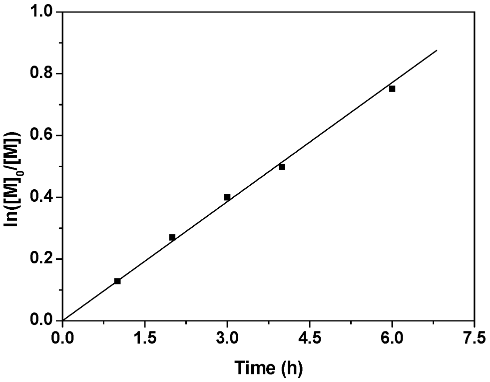


Figure 5. First-order kinetic plot for ATRP of MMA initiated with CMG3-PLLABr. $[M]_0:[I]_0:[CuBr]_0:[PMDETA]_0 = 100:1:1:1$, $[M]_0 = 2.0$ M, in anisole at 80 °C.

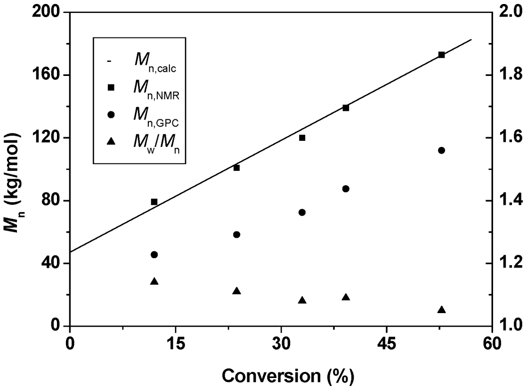


Figure 6. Evolution of M_n and M_w/M_n of CMG3-PLLA-*b*-PMMA with conversion for ATRP of MMA. See Figure 5 for reaction conditions.

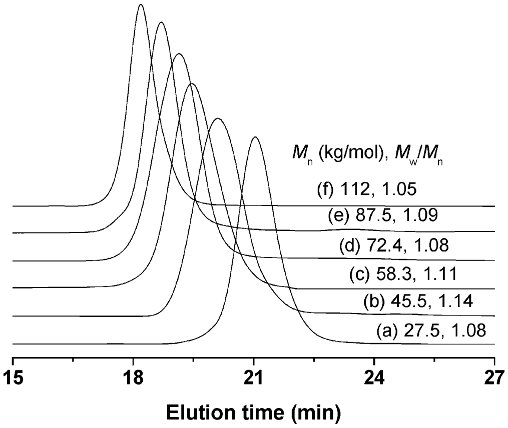


Figure 7. GPC traces of CMG3-PLLABr (a) and CMG3-PLLA-*b*-PMMA (b−f).

kinetics was investigated in detail. Figure 5 indicates the first-order kinetics could be maintained until high conversion, suggesting the concentration of active species remained constant throughout the course of polymerization. The dependence of molecular weight and molecular weight distribution of the star block copolymers on conversion is plotted in Figure 6. $M_{n,NMR}$ values, which are close to the calculated values at various conversions, increase linearly with conversion, indicating the molecular weight of the resulting copolymer could be manipulated by the control of monomer conversion. The molecular weight distribution ($1.05 < M_w/M_n < 1.14$) is narrow, and no obvious shoulders and tailings are observed in GPC traces (Figure 7), suggesting the high initiation efficiency and negligible radical−radical coupling in polymerization. The above results indicate CMG3-PLLABr could be used as an efficient initiator for living polymerization of MMA.

CMG*n*-PLLABr as Macroinitiator for ATRP of Styrene. Until now, the synthesis of well-defined multiarmed star PSt with core-first approach via controlled radical polymerization is still a challenge due to the existence of coupling reaction at high conversion.[10,24,25,29] In general, regular multiarmed star PSt by this approach can be achieved at the cost of low conversion; otherwise, the coupling reaction will take place and results in uncontrolled polymerization.[10,24,25] For instance, Angot et al. reported the ATRP of St using an octafunctional initiator and found that the controlled polymerization could be maintained at low conversion, typically below 15−20%.[10,24] Haddleton's group investigated the synthesis of 21-armed star PSt and found a shoulder peak in GPC traces was observed for polymers obtained at 11% conversion.[25] In this study, the ATRP of styrene using CMG*n*-PLLABr macroinitiator was conducted at 100 °C in bulk and anisole. From Table 3 it is found the living polymerization could be performed under low conversion, which is consistent with the results reported by Angot et al.[10,24] The critical conversion (CC) beyond which the molecular weight control is lost and the semilogarithmic kinetic plot gradually departs from the original linear relationship was estimated by combination of GPC and kinetic analysis, and a shoulder peak was always observed in the GPC traces of copolymers obtained at conversion above CC. When polymerization with $[M]_0/[I]_0$ ranging from 200 to 1000 was carried out under various conditions, the CC values were found to vary from 5% to 30% and strongly depended on the functionality of macroinitiators and

Table 3. Results for ATRP of St with CMG*n*-PLLABr Initiator under Various Conditions

						M_n (kg/mol)				
sample	initiator	ratio[a]	solvent	time (h)	C (%)	$M_{n,calc}$[b]	$M_{n,NMR}$[c]	$M_{n,GPC}$[d]	M_w/M_n[d]	CC (%)[e]
1	CMG1-PLLABr	200:1:1:1	bulk	3	24.6	59.6	62.4	54.8	1.12	~30
2	CMG1-PLLABr	500:1:1:1	anisole	4	11.4	90.7	92.5	78.0	1.18	~28
3	CMG1-PLLABr	1000:1:1:1	anisole	4	10.8	123	120	108	1.10	~32
4	CMG2-PLLABr	200:1:1:1	bulk	3	20.7	107	115	83.6	1.11	~27
5	CMG2-PLLABr	200:1:1:1	anisole	4	11.2	83.1	87.2	62.5	1.15	~20
6	CMG2-PLLABr	800:1:1:1	anisole	6	14.0	195	204	148	1.12	~25
7	CMG3-PLLABr	200:1:1:1	bulk	2	17.8	136	148	89.6	1.10	~18
8	CMG3-PLLABr	200:1:1:1	anisole	3	8.0	86.8	88.2	58.8	1.08	~12
9	CMG3-PLLABr	400:2:1:1	anisole	3	6.2	77.8	73.2	50.6	1.08	~15
10	CMG3-PLLABr	800:4:1:1	anisole	4	6.6	79.8	82.5	51.2	1.12	~16
11	CMG3-PLLABr	400:1:1:1	anisole	3	7.4	121	125	82.7	1.09	~16
12	CMG3-PLLABr	1000:1:1:1	anisole	4	6.8	217	208	125	1.12	~20

[a] Molar ratio of $[M]_0:[I]_0:[CuBr]_0:[PMDETA]_0$, $T = 100$ °C, and $[M]_0 = 2.0$ M in solution polymerization, where $[I]_0$ stands for the concentration of all the initiation sites. [b] Calculated from $M_{n,calc} = 104.15 \times ([M]_0/[CMGn\text{-PLLABr}]_0) \times C\% + M_{winitiator}$. [c] Determined by ^{1}H NMR, the average chain length of PSt was estimated by comparison of signal intensity ratios of methine protons of PLLA (5.17 ppm) to PhH protons of PSt (6.2−7.2 ppm) based on the DP value of PLLA. [d] Estimated by GPC calibrated by PS standard, and no obvious shoulder peak was observed in GPC traces for all samples. [e] Critical conversion estimated by GPC traces and polymerization kinetics analysis.

reaction conditions such as types of polymerization (in bulk or solution), temperature, monomer-to-initiator ratios, and the amount of catalyst (Table 3). In general, lowering functionality of initiators, reaction temperature, and amount of catalyst and increasing monomer-to-initiator ratios are liable to enhance the CC values. As compared with the solution polymerization, the polymerization conducted in bulk possesses a higher CC value presumably due to the increased mobility of the reactive chain ends in solution.[10,13,24] When the functionality of macroinitiators increased from 6 to 24, the maximum CC values were estimated to decrease from 32% to 20%, indicating the influence of increasing branching degree on the motion of reactive chain ends and the dynamics of activation/deactivation of multifunctional systems.[10,24] When polymerization was conducted at 100 °C in bulk with feed ratios of $[M]_0:[I]_0:[CuBr]_0:[PMDETA]_0 = 200:1:1:1$, the CC value was determined to be about 18%, while it decreased to be 5% as the reaction temperature increased to 110 °C presumably due to the obviously increased mobility of the reactive chain ends with increasing temperature. For polymerization conducted at 100 °C in anisole with $[I]_0:[CuBr]_0:[PMDETA]_0 = 1:1:1$, the CC value increased from 12% to 20% as $[M]_0/[I]_0$ increased from 200 to 1000, while the chain length of PSt was apparently enhanced. When $[M]_0/[I]_0 = 200$ and $[I]_0:[CuBr]_0:[PMDETA]_0$ varied from 1:1:1 to 4:1:1, the CC value increased from 12% to 16%. The above results indicate the optimal reaction conditions are crucial to the formation of high-molecular-weight star PLLA−PSt block copolymers.

When CMG3-PLLABr was used as macroinitiator for ATRP of styrene ($[M]_0:[I]_0:[CuBr]_0:[PMDETA]_0 = 200:1:1:1$), the polymerization kinetics was investigated in detail. The semilogarithmic kinetic plot is shown in Figure 8, and the dependence of M_n and M_w/M_n of CMG3-PLLA-*b*-PSt on monomer conversion is described in Figure 9. As the conversion is less than 12%, the polymerization took place smoothly, and the first-order polymerization kinetics is maintained. In this period, the polymerization is of living nature, the GPC traces (Figure 10b−f) are symmetrical and unimodal, and well-defined CMG3-PLLA-*b*-PSt with predetermined molecular weight and narrow molecular weight distribution ($1.06 < M_w/M_n < 1.12$) can be reached by the manipulation of monomer conversion. Meanwhile, the plots of $M_{n,GPC}$ and $M_{n,NMR}$ vs monomer conversion keep a good linear relationship. Beyond 12% conversion, the molecular weight control is lost and the plot of $M_{n,GPC}$ vs monomer conversion strongly departs from the original linear relationship, and a shoulder is observed in the high molecular weight side of the GPC traces (Figure 10g,h); this phenomenon can be attributed to the irreversible star−star coupling and intrastar termination.[10,24] In this case, however, the ^{1}H NMR approach is difficult to afford the precise number-average molecular weight since it does not take account of the increasing average arm numbers in star polymers. The above results indicate well-defined CMG3-PLLA-*b*-PSt could be achieved using the CMG3-PLLABr/CuBr/

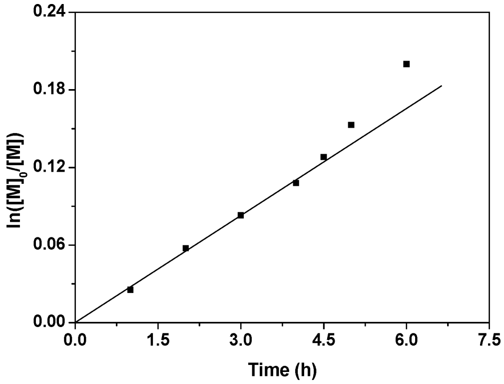


Figure 8. Semilogarithmic kinetic plot for ATRP of St with CMG3-PLLABr initiator. $[M]_0:[I]_0:[CuBr]_0:[PMDETA]_0 = 200:1:1:1$, $[M]_0 = 2.0$ M, in anisole at 100 °C.

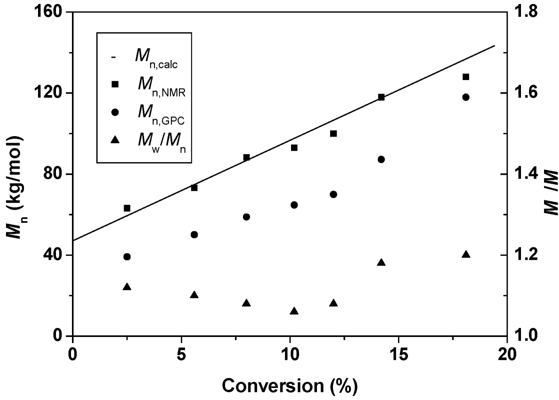


Figure 9. Dependence of M_n and M_w/M_n of CMG3-PLLA-*b*-PSt on conversion. See Figure 8 for reaction conditions.

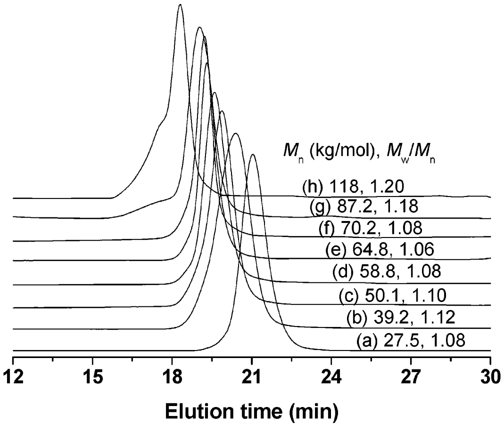


Figure 10. GPC traces of CMG3-PLLABr (a) and CMG3-PLLA-*b*-PSt (b–h).

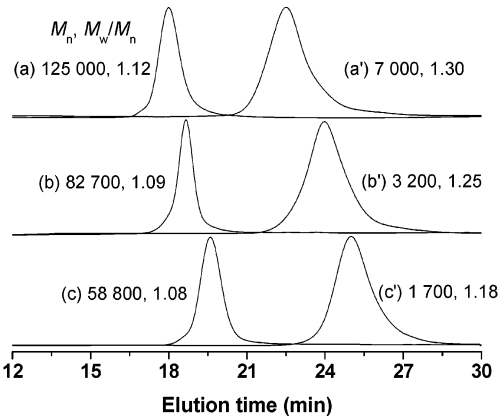


Figure 11. Comparison of GPC traces of CMG3-PLLA-*b*-PSts (a–c) and their corresponding hydrolyzed linear PSt (a′–c′).

PMDETA initiating system by stopping the polymerization at a low conversion.

Hydrolysis of CMG*n*-PLLA-*b*-PSt. For star polymers, it is necessary to verify whether each of the alkyl halide fragments of the initiators had participated in the ATRP process since incomplete initiation during the course of polymerization was detected in some cases.[13] So far, the methods to determine the precise arm numbers in star polymers primarily include hydrolysis approach,[8,10,24,25] kinetic approach,[11] mixed initiator approach,[10,24] ^{1}H NMR spectra approach using partially deuterated monomer,[13] and function approach utilizing multidetector SEC.[26] Among them, the hydrolysis approach has proven to be a most efficient one to determine the number of branches in a star structure. In this study, the hydrolysis approach was used to determine the functionality of star block copolymers. Various CMG*n*-PLLA-*b*-PSt samples were thus hydrolyzed using KOH, and the resulting linear PSt was isolated and analyzed by GPC. As a comparison, typical GPC traces of CMG3-PLLA-*b*-PSt precursors (a–c) and the remaining arms (a′–c′) are shown in Figure 11. All the PSt arms exhibit monomodal distribution and relatively narrow molecular weight distribution ($1.15 < M_w/M_n < 1.32$), indicating the absence of higher-molecular-weight byproduct. In some cases, the tailing curves of the isolated PSt arms are observed especially for linear PSt samples hydrolyzed from high-molecular-weight star block copolymers, suggesting that some side reactions such as termination and transfer reactions during polymerization have occurred to a nonnegligible extent. The existence of the above side reactions at low conversions may be ascribed to the particular topology of star polymers and its influence on the motion of reactive ends as well as the dynamics of activation/deactivation of multifunctional systems.[10,24] In addition, the M_w/M_n of the cleaved arm polymer is higher than that of the original star polymer, and similar tendencies have been observed by other groups,[8,10,25] which are consistent with the theoretical expectation. As expected, the M_w/M_n's of star-branched polymer have a reciprocal relation to arm number, and the overall molecular weight distribution of star polymer is lower than that of star polymer arm.[64,65] The results listed in Table 4 indicate that experimental molecular weight of linear PSt is in good agreement with the theoretically calculated value based on feed ratio and conversion, demonstrating the CMG*n*-PLLABrs could quantitatively initiate the ATRP of styrene, and star PLLA–PSt block copolymers with arm number of 6, 12, and 24 have been successfully achieved.

Table 4. Hydrolysis Results of CMG*n*-PLLA-*b*-PSt with Various Arm Numbers

sample[a]	F[b]	$[M]_0/[I]_0$	C (%)	$M_{n,calc}$[c]	$M_{n,GPC}$[d]	M_w/M_n[d]
1	6	200	24.6	5200	5000	1.24
2	6	500	11.4	6000	6400	1.32
3	6	1000	10.8	11300	10800	1.20
4	12	200	20.7	4400	4200	1.28
5	12	200	11.2	2400	2500	1.35
6	12	800	14.0	11800	12000	1.27
8	24	200	8.0	1800	1700	1.18
11	24	400	7.4	3200	3200	1.25
12	24	1000	6.8	7200	7000	1.30

[a] Samples as listed in Table 3. [b] Theoretical arm numbers of star block copolymers. [c] Calculated from feed ratio and conversion. [d] GPC results for hydrolyzed linear PSt.

Conclusions

A series of dendrimer-like star polylactides and star block copolymers up to 24 arm were successfully synthesized in this study. Star polylactides with expected molecular weights and narrow molecular weight distributions were synthesized by living ROP of L-lactide in the presence of poly(aryl ether) dendrimer initiators and stannous octoate catalyst in bulk at 120 °C. ATRP using CMG*n*-PLLABr/CuBr/PMDETA initiating system under suitable conditions afforded well-defined star block copolymers such as CMG*n*-PLLA-*b*-PMMA and CMG*n*-PLLA-*b*-PSt. The resultant star PLLAs and star block copolymers possessed precise arm numbers of 6, 12, and 24, which was demonstrated by NMR spectra analysis and hydrolysis approach, respectively. The physical properties of these copolymers are currently in progress and will be described in a future publication.

Acknowledgment. The financial support to this work by the National Natural Science Foundation of China (Grants 50073026 and 50273042) and the fund of Polymer Chemistry Laboratory, Chinese Academy of Sciences and China Petro-Chemical Corporation, is gratefully acknowledged.

References and Notes

(1) Matyjaszewski, K.; Xia, J. *Chem. Rev.* **2001**, *101*, 2921.
(2) Hawker, C. J.; Bosman, A. W.; Harth, E. *Chem. Rev.* **2001**, *101*, 3661.
(3) Kamigaito, M.; Ando, T.; Sawamoto, M. *Chem. Rev.* **2001**, *101*, 3689.
(4) Hadjichristidis, N.; Pitsikalis, M.; Pispas, S.; Iatrou, H. *Chem. Rev.* **2001**, *101*, 3747.
(5) Kennedy, J. P.; Jacob, S. *Acc. Chem. Res.* **1998**, *31*, 835.

(6) Ishizu, K. *Prog. Polym. Sci.* **1998**, *23*, 1383.
(7) Inoue, K. *Prog. Polym. Sci.* **2000**, *25*, 453.
(8) Ueda, J.; Kamigaito, M.; Sawamoto, M. *Macromolecules* **1998**, *31*, 6762.
(9) Ueda, J.; Matsuyama, M.; Kamigaito, M.; Sawamoto, M. *Macromolecules* **1998**, *31*, 557.
(10) Angot, S.; Murthy, K. S.; Taton, D.; Gnanou, Y. *Macromolecules* **1998**, *31*, 7218.
(11) Matyjaszewski, K.; Miller, P. J.; Pyun, J.; Kickelbick, G.; Diamanti, S. *Macromolecules* **1999**, *32*, 6526.
(12) Heise, A.; Hedrick, J. L.; Frank, C. W.; Miller, R. D. *J. Am. Chem. Soc.* **1999**, *121*, 8647.
(13) Heise, A.; Diamanti, S.; Hedrick, J. L.; Frank, C. W.; Miller, R. D. *Macromolecules* **2001**, *34*, 3798.
(14) Kanaoka, S.; Sawamoto, M.; Higashimura, T. *Macromolecules* **1991**, *24*, 2309.
(15) Xia, J.; Zhang, X.; Matyjaszewski, K. *Macromolecules* **1999**, *32*, 4482.
(16) Zhang, X.; Xia, J. H.; Matyjaszewski, K. *Macromolecules* **2000**, *33*, 2340.
(17) Baek, K. Y.; Kamigaito, M.; Sawamoto, M. *Macromolecules* **2001**, *34*, 215.
(18) Baek, K. Y.; Kamigaito, M.; Sawamoto, M. *Macromolecules* **2001**, *34*, 7629.
(19) Baek, K. Y.; Kamigaito, M.; Sawamoto, M. *J. Polym. Sci., Part A: Polym. Chem.* **2002**, *40*, 2245.
(20) Bosman, A. W.; Vestberg, R.; Heumann, A.; Fréchet, J. M. J.; Hawker, C. J. *J. Am. Chem. Soc.* **2003**, *125*, 715.
(21) Heise, A.; Hedrick, J. L.; Trollsås, M.; Miller, R. D.; Frank, C. W. *Macromolecules* **1999**, *32*, 231.
(22) Heise, A.; Nguyen, C.; Malek, R.; Hedrick, J. L.; Frank, C. W.; Miller, R. D. *Macromolecules* **2000**, *33*, 2346.
(23) Hovestad, N. J.; van Koten, G.; Bon, S. A. F.; Haddleton, D. M. *Macromolecules* **2000**, *33*, 4048.
(24) Angot, S.; Murthy, K. S.; Taton, D.; Gnanou, Y. *Macromolecules* **2000**, *33*, 7261.
(25) Ohno, K.; Wong, B.; Haddleton, D. M. *J. Polym. Sci., Part A: Polym. Chem.* **2001**, *39*, 2206.
(26) Robello, D. R.; André, A.; McCovick, T. A.; Kraus, A.; Mourey, T. H. *Macromolecules* **2002**, *35*, 9334.
(27) Percec, V.; Barboiu, B.; Grigoras, C.; Bera, T. K. *J. Am. Chem. Soc.* **2003**, *125*, 6503.
(28) Beil, J. B.; Zimmerman, S. C. *Macromolecules* **2004**, *37*, 778.
(29) Zhao, Y. L.; Chen, Y. M.; Chen, C. F.; Xi, F. *J. Polym. Sci., Part A: Polym. Chem.,* in press.
(30) Feng, X. S.; Pan, C. Y. *Macromolecules* **2002**, *35*, 2084.
(31) Heise, A.; Trollsås, M.; Magbitang, T.; Hedrick, J. L.; Frank, C. W.; Miller, R. D. *Macromolecules* **2001**, *34*, 2798.
(32) Erdogan, T.; Ozyurek, Z.; Hizal, G.; Tunca, U. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 2313.
(33) He, T.; Li, D. J.; Sheng, X.; Zhao, B. *Macromolecules* **2004**, *37*, 3128.
(34) Hedrick, J. L.; Trollsås, M.; Hawker, C. J.; Atthoff, B.; Claesson, H.; Heise, A.; Miller, R. D.; Mecerreyes, D.; Jérôme, R.; Dubois, Ph. *Macromolecules* **1998**, *31*, 8691.
(35) Francis, R.; Taton, D.; Logan, J. L.; Masse, P.; Gnanou, Y.; Duran, R. S. *Macromolecules* **2003**, *36*, 8253.
(36) Hou, S. J.; Chaikof, E. L.; Taton, D.; Gnanou, Y. *Macromolecules* **2003**, *36*, 3874.
(37) Johnson, R. M.; Fraser, C. L. *Biomacromolecules* **2004**, *5*, 580.
(38) Johnson, R. M.; Fraser, C. L. *Macromolecules* **2004**, *37*, 2718.
(39) Zhao, Y. L.; Shuai, X. T.; Chen, C. F.; Xi, F. *Chem. Commun.* **2004**, 1608.
(40) Uhrich, K. E.; Cannizzaro, S. M.; Langer, R. S.; Shakesheff, K. M. *Chem. Rev.* **1999**, *99*, 3181.
(41) Albertsson, A. C.; Varma, I. K. *Biomacromolecules* **2003**, *4*, 1466.
(42) Lou, X. D.; Detrembleur, C.; Jérôme, R. *Macromol. Rapid Commun.* **2003**, *24*, 161.
(43) Breitenbath, A.; Kissel, T. *Polymer* **1998**, *39*, 3261.
(44) Breitenbath, A.; Pistel, K. F.; Kissel, T. *Polymer* **2000**, *41*, 4781.
(45) Dubois, P.; Degée, P.; Jérôme, R.; Teyssié, P. *Macromolecules* **1992**, *25*, 2614.
(46) Choi, Y. K.; Bae, Y. H.; Kim, S. W. *Macromolecules* **1998**, *31*, 8766.
(47) Finne, A.; Albertsson, A. C. *Biomacromolecules* **2002**, *3*, 684.
(48) Korhonen, H.; Helminen, A.; Seppälä, J. V. *Polymer* **2001**, *42*, 7541.
(49) Zhao, Y. L.; Cai, Q.; Jiang, J.; Shuai, X. T.; Bei, J. Z.; Chen, C. F.; Xi, F. *Polymer* **2002**, *43*, 5819.
(50) Zhao, Y. L.; Shuai, X. T.; Chen, C. F.; Xi, F. *Chem. Mater.* **2003**, *15*, 2836.
(51) Cai, Q.; Zhao, Y. L.; Bei, J. Z.; Xi, F.; Wang, S. G. *Biomacromolecules* **2003**, *4*, 828.
(52) Kricheldorf, H. R.; Hachmann-Thiessen, H.; Schwarz, G. *Biomacromolecules* **2004**, *5*, 492.
(53) Ydens, I.; Degée, P.; Dubois, Ph.; Libiszowski, J.; Duda, A.; Penczek, S. *Macromol. Chem. Phys.* **2003**, *204*, 171.
(54) Teramoto, Y.; Nishio, Y. *Polymer* **2003**, *44*, 2701.
(55) Nouvel, C.; Dubois, Ph.; Dellacherie, E.; Six, J. L. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 2577.
(56) Trollsås, M.; Atthoff, B.; Claesson, H.; Hedrick, J. L. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 1174.
(57) Matyjaszewski, K.; Qin, S.; Boyce, J. R.; Shirvanyants, D.; Sheiko, S. S. *Macromolecules* **2003**, *36*, 1843.
(58) Bosman, A. W.; Bruining, M. J.; Kooijman, H.; Spek, A. L.; Janssen, R. A. J.; Meijer, E. W. *J. Am. Chem. Soc.* **1998**, *120*, 8547.
(59) Hawker, C. J.; Wooley, K. L.; Fréchet, J. M. J. *J. Chem. Soc., Perkin Trans 1* **1993**, 1287.
(60) Fischer, E. W.; Sterzel, H. J.; Wegner, G. *Kolloid Z. Z. Polym.* **1973**, *251*, 980.
(61) Grayson, S. M.; Fréchet, J. M. J. *Chem. Rev.* **2001**, *101*, 3819.
(62) Fréchet, J. M. J.; Tomalia, D. A. *Dendrimers and Other Dendritic Polymers*; John Wiley & Sons: New York, 2001.
(63) Newkome, G. R.; Moorefield, C. N.; Vögtle, F. *Dendrimers and Dendrons-Concepts, Syntheses, and Applications*; Wiley-VCH: Weinheim, 2001.
(64) Flory, P. J. *J. Am. Chem. Soc.* **1952**, *74*, 2718.
(65) Szymanski, R. *Macromolecules* **2002**, *35*, 8239.

MA048303R