

Synthesis of novel dendrimer-like star block copolymers with definite numbers of arms by combination of ROP and ATRP†

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Well-defined biodegradable dendrimer-like star block copolymers with up to 24 arms were successfully synthesized by combination of living ring-opening polymerization (ROP) and atom transfer radical polymerization (ATRP) on the basis of dendritic benzyl alcohols.

Aliphatic polyesters such as polylactide and its copolymers are an important class of biologically relevant polymers. Many approaches have been attempted to modify the physical properties of poly(L-lactide) (PLLA) due to its high crystallinity and poor controlled degradation. Among them, the introduction of branched structures is an effective method.^{1–3} Since well-defined architectures are essential to elucidate the relationship among branched structures and physical properties, the synthesis of regular star polymers with definite number of arms has attracted much attention.^{4–6} More recently, great attention has been paid to combination of various living polymerization approaches by mechanism transformation.^{7–10} The “combinatorial” techniques not only enrich the types of polymerizable monomers, but can be used to prepare well-defined block and graft copolymers with variable compositions, structures and properties.

Although regular dendritic star poly lactides with up to 24 arms have been successfully synthesized by Hedrick and coworkers,¹¹ the phenomenon of incomplete initiation was observed for ROP of lactide as the initiators possessed a higher functionality (e.g. eight).^{2,3,12,13} For instance, when PAMAM-OH dendrimers were used as macroinitiators, the graft efficiency significantly decreased with an increase in generation of dendrimers.² In effect, the synthesis of regular star polymers is dependent upon some factors such as steric hindrance, initiation conditions^{14,15} and the nature of the initiators.¹⁶ In some cases, backfolding of the dendrimer periphery may occur,¹⁶ which can also lead to low graft efficiency.

In this study, novel polyaryl ether dendrimers (CMG n -OH, $n = 1–3$) with 1,3,5-tri(4-hydroxyphenoxy)benzene cores, polybenzyl ether interiors and benzyl alcohol surface groups were designed and synthesized in order to prepare star polymers with higher numbers of arms. These dendrimers possess relatively large molecular size and rigidity and are expected to avoid the backfolding of functional end groups and decrease the steric effect in polymerization. To evaluate the possibility of all-terminal hydroxy groups in dendrimer initiators starting growth of polylactide, use of dendritic benzyl alcohols up to the third generation (Scheme 1) as initiators for ROP of L-lactide (LLA) in the presence of stannous octoate catalyst, were chosen. Meanwhile, novel star block copolymers were synthesized by mechanism transformation.

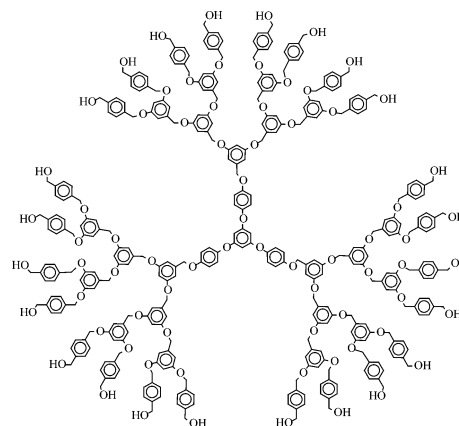
For ROP of L-lactide, 120 °C is found to be the most suitable reaction temperature, and the dendrimer-like star poly lactides (CMG n -PLLAs) with predetermined molecular weight and low polydispersity can be formed under suitable conditions. Moreover, it is found that all the hydroxy groups on the surface of dendrimer initiators initiated the polymerization. In ¹H NMR spectra of star

PLLAs obtained at various conversions, the signal corresponding to PhCH₂OH protons of the dendrimer initiator (4.50 ppm) completely disappeared, while the signal of PhCH₂O at 5.01 ppm was correspondingly enhanced. Meanwhile, no signal at 64.4 ppm (PhCH₂OH) or 143.3 ppm (PhC–CH₂OH) was observed in ¹³C NMR spectra, while new signals appeared at 66.0 ppm (PhCH₂OPLLA) and 135.8 ppm (PhC–CH₂OPLLA). Both results demonstrated that all the hydroxy groups had quantitatively initiated the polymerization.

For various amounts of initiators, the polymerization results are summarized in Table 1. As a comparison, the molecular weights of the resultant polymers were also measured by GPC, ¹H NMR and light scattering. For various samples, the difference between $M_{n,NMR}$ and $M_{n,GPC}$ is dependent on the number of arms, which can be ascribed to the distinct hydrodynamic volumes between star polymers and linear PSt. Taking account of the polydispersities of star PLLAs, the $M_{n,NMR}$ values are close to the absolute $M_{w,SLS}$ values. Both are in good agreement with the theoretically calculated molecular weights, and the polydispersities are quite low ($1.06 < M_w/M_n < 1.15$), 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 the molar ratio of monomer to initiator ([LA]/[OH]) is shown in Fig. 1. The molecular weight linearly increases with the increase in [LA]/[OH], confirming the role of the hydroxy groups on dendrimer surfaces as effective propagation centers. The above result also suggests that the molecular weight of star PLLAs can be manipulated by the variation of molar ratio of monomer to initiator.

Moreover, 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 Fig. 2. The star polymers exhibit molecular weights close to the expected values, revealing the high initiation activity of dendrimer initiators. The molecular weight linearly increases with conversion, while the polydispersities are low ($M_w/M_n < 1.10$). The GPC traces are symmetrical and monomodal, indicating the absence of linear polylactide and negligible side reactions such as transesterification and thermal degradation during polymerization.



Scheme 1 Structure of CMG3-OH.

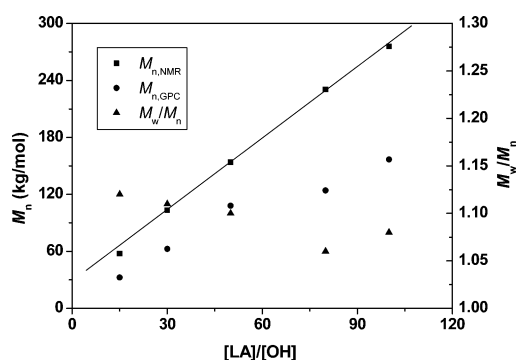
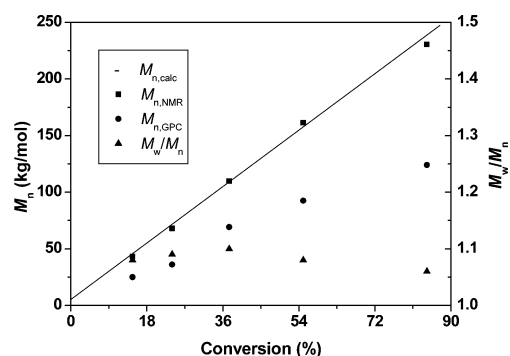
† Electronic supplementary information (ESI) available: Complete experimental procedures; NMR spectra of CMG3-OH and CMG3-PLLA. See <http://www.rsc.org/suppdata/cc/b4/b404143g/>

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Table 1 Polymerization results of L-lactide using CMG n -OH initiators^a

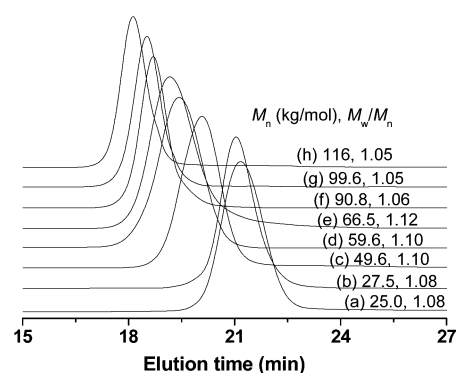
Initiator	F^b	R^c	C (%)	$M_{n,calc}/\text{kg mol}^{-1}$	$M_{n,NMR}/\text{kg mol}^{-1}$	$M_{n,GPC}^d / \text{kg mol}^{-1}$	PDI ^d	$M_{w,SLS}^e / \text{kg mol}^{-1}$
CMG1-OH	6	30	95.0	26.1	28	42.7	1.12	30.5
CMG1-OH	6	50	92.4	41.4	43	66.6	1.09	47.2
CMG1-OH	6	80	88.8	62.8	63	93.6	1.10	69.0
CMG2-OH	12	30	96.4	52.9	53	52.8	1.15	62.4
CMG2-OH	12	50	94.8	84.8	81	84.3	1.08	88.7
CMG2-OH	12	80	90.0	127	120	124	1.06	133
CMG3-OH	24	30	97.3	107	103	62.4	1.11	118
CMG3-OH	24	50	90.5	162	154	88.7	1.10	176
CMG3-OH	24	80	84.3	239	231	124	1.06	248

^a [LA]/[SnOct₂] = 500, 24 h, in bulk at 120 °C. ^b Functionality of dendrimer initiators. ^c Feed ratio of [LA]/[OH]. ^d Determined by GPC using polystyrene calibration. ^e Determined by light scattering.

**Fig. 1** Dependence of molecular weight and polydispersity of CMG3-PLLA on [LA]/[OH]; [LA]/[SnOct₂] = 500, 120 °C, 24 h.**Fig. 2** Polymerization results at various monomer conversions. Reaction conditions: [LA]:[OH]:[SnOct₂] = 80:1:0.16, 120 °C.

CMG n -PLLA can be converted into a macroinitiator CMG n -PLLABr *via* esterification with 2-bromoisobutyryl bromide. In ¹H NMR spectra, the signals at 4.37 ppm (terminal CH) and 2.64 ppm (terminal OH) wholly disappeared, and a novel signal corresponding to C(Br)(CH₃)₂ protons appeared at 1.98 ppm, revealing that all the terminal hydroxy groups have been quantitatively functionalized. Novel biodegradable dendrimer-like star block copolymers such as CMG n -PLLA-*b*-PSt, CMG n -PLLA-*b*-PMMA and CMG n -PLLA-*b*-PtBA with definite numbers of arms can be achieved by ATRP of styrene (St), methyl methacrylate (MMA) and *tert*-butyl acrylate (*t*BA) using CMG n -PLLABr macroinitiator. When CMG3-PLLABr ($M_n = 27.5 \text{ kg mol}^{-1}$, $M_w/M_n = 1.08$) was used to initiate ATRP of various monomers with the CuBr/pentamethyldiethylenetriamine (PMDETA) catalytic system, the GPC traces of the macroinitiator and star block copolymers shown in Fig. 3 resulted. The molecular weights of various star block copolymers remarkably increased with increasing monomer conversion, and no shoulders or tails were observed, suggesting high blocking efficiency.

In conclusion, a series of well-defined dendrimer-like star PLLAs and star block copolymers with up to 24 arms were achieved in this study. Their physicochemical properties are

**Fig. 3** GPC traces of CMG3-PLLA (a), CMG3-PLLABr (b), CMG3-PLLA-*b*-PtBA (c, h), CMG3-PLLA-*b*-PSt (e, g) and CMG3-PLLA-*b*-PMMA (d, f). Polymerization conditions: [M]:[24[CMG3-PLLABr]]:[CuBr]:[PMDETA] = 150:1:1:1, in bulk, and (c) 80 °C, 1 h; (d) 80 °C, 20 min; (e) 100 °C, 1 h; (f) 80 °C, 1 h; (g) 100 °C, 2 h; (h) 80 °C, 6 h.

currently under investigation and will be reported in a future publication.

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