Synthesis of Biomimetic Poly(hydroxybutyrate): Alkoxy- and Carboxytriazolines as Latent Ionic Initiator

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ABSTRACT: A well-defined high molecular weight poly(3-hydroxybutyrate) was synthesized by "living"/controlled ring-opening polymerization (ROP) of β-butyrolactone (BL) using a metal-free catalytic system. The ROP was initiated from either primary alcohol or carboxylic acid added with 1 equiv of a stable carbene, i.e., 1,3,4-triphenyl-4,5-dihydro-1*H*-1,2,4-triazol-5-ylidene carbene, **1**. Interestingly, perfect control over molecular weight (M_n up to 32 000 g·mol^{-1}), molecular weight distribution ($M_w/M_n \sim 1.1 - 1.3$) and end group fidelity was attained using *t*-BuOH as the only polymerization solvent at 80 °C. Structural and kinetics studies highlighted an anionic polymerization mechanism where the protonated **1** (**1**-H) played the role of associated counterion. Attesting for the control of the ROP, amphiphilic block copolymers were further synthesized by polymerization of BL from poly(ethylene oxide) α-methoxy, ω-carboxylic acid macroinitiator while their tensioactive properties were evidenced by the pendant drop method.

Introduction

Poly(hydroxyalkanoate)s are an important class of biomacromolecules that are produced by a wide variety of microorganisms and used as metabolic storage materials or in the metal ion transportation. Since poly[(*R*)-(−)-3-hydroxybutyrate] (PHB) was discovered in 1926, this family of biopolymers has been significantly expanded by controlled fermentation. However, the high cost associated with the fermentation process prevented competition with the less expensive synthetic, petrochemical-based materials.[1] An alternative entry to PHBs involves the ring-opening polymerization (ROP) of β-butyrolactone (BL), where isotactic PHB can be prepared from the enantiomerically pure monomer and atactic PHB from the racemic monomer, as well as the possibility of PHB with diads enhanced with either syndiotactic or isotactic sequences. As discussed in numerous papers, ROP can proceed by bond breaking either between the β-carbon and oxygen atom of the β-lactone ring (O-alkyl cleavage) or between the carbonyl carbon and the oxygen atom (O-acyl cleavage) when polymerization is initiated by carboxylate or alcoholate active centers, respectively.[2] However, depending on the polymerization solvent and the nature of the alkoxide initiator, the formation of both alcoholate and carboxylate active species (formed in nearly equal proportions) at the initiation stage of the β-lactone polymerization was observed by Penczek et al. (Scheme 1).[3]

The use of nucleophiles to accomplish acyl cleavage implies that these reagents are also basic and can give rise to competitive elimination reactions. The crotonate byproducts that result are themselves initiators for polymerization of BL by alkyl cleavage, leading to loss of control and end group fidelity.[4] Interestingly Jedlinski et al. employed carboxylic acid salts with bulky tetrabutyl ammonium counterions leading to high molecular weight polymers (DP ≤ 2000) even if crotonates were observed in the reaction medium.[5a] Although there is a considerable number of reports on the ROP of BL, and comparatively to the non-organometallic system, only a few recent examples using either distannoxane or zinc complexes as organometallic promoters have demonstrate the synthesis of narrowly dispersed PHB of high molecular weight.[5b] However, crotonate formation and hence end group fidelity still remains a problem for these catalyst systems. Some of us have recently reported on the controlled ROP of BL as catalyzed by the 1,3,4-triphenyl-4,5-dihydro-1*H*-1,2,4-triazol-5-ylidene carbene, **1**, in toluene at 80 °C.[6] It has been shown that the catalytic activity of **1** could be largely increased by the simple addition of *t*-BuOH to the reaction medium. The role of *t*-BuOH has been previously investigated and recently reported.[6] Briefly, the triazole carbene **1** is actually characterized by a quite important inherent basicity leading to undesired elimination reactions directly from the BL monomer and generating crotonate derivatives in the reaction medium. It has been further evidenced that bulky tertiary alcohol, such as *t*-BuOH cannot initiate the polymerization of cyclic esters like BL. However, the use of **1** with *t*-BuOH as a cosolvent, intended to enhance nucleophilic attack over detrimental deprotonation side reactions and to minimize crotonate formation, was successful for the polymerization of BL for molecular weight targets below 15 000 g mol^{-1}, but the control (i.e., end group fidelity) was compromised for higher targeted molecular weights.[6] Such unfortunate results stimulated us to examine again the process of BL polymerization by using **1** as catalyst and *t*-BuOH as the only polymerization solvent.

Herein we report on the control polymerization of BL from an equimolar mixture of primary alcohol and carbene **1** (alkoxyadduct) in terms of molecular weight and end group fidelity using *t*-BuOH as the only polymerization solvent. Since

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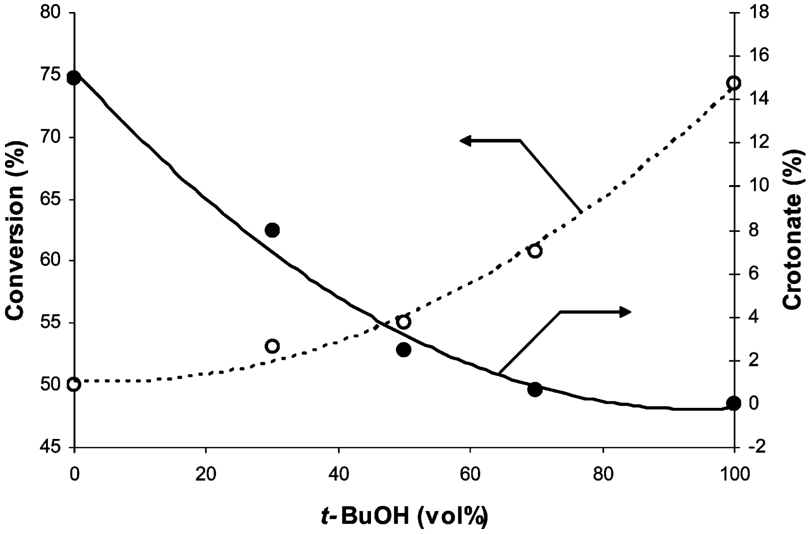
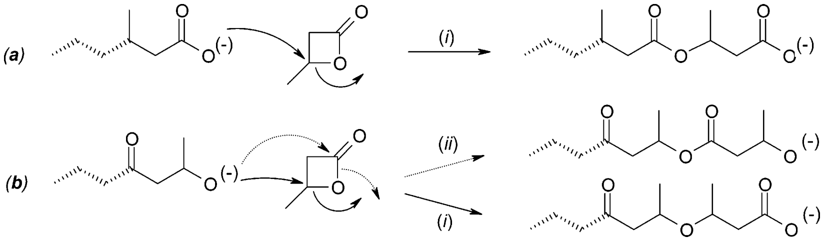


Figure 1. Final conversions and crotonate end group percentages obtained after polymerization of BL initiated by MeOH/**1** at 80 °C for 25 min in different toluene-to-*t*-BuOH mixtures ($[BL]_0 = 5$ mol L^{-1}).

Scheme 1. Alkyl (i) and Acyl (ii) Cleavages of BL from Carboxylate (a) and Alcoholate Propagating Centers (b)



two monomer cleavages ("*O*-acyl" and "*O*-alkyl") have been observed during the BL propagation from alkoxyadduct initiators, the polymerization from carboxyadducts ($[R-COOH]_0/[\mathbf{1}]_0 = 1$) has also been investigated. Finally, amphiphilic block copolymers have been synthesized by polymerization of BL from the poly(ethylene oxide) α-methoxy-*ω*-carboxylic acid (PEO−COOH) macroinitiator while tensioactive properties have been determined by the pendant drop method.

Results and Discussion

Homopolymerization from Alkoxy- and Carboxy Adducts. Polymerization of [*R*,*S*]-*β*-butyrolactone (BL) by 1,3,4-triphenyl-4,5-dihydro-1*H*-1,2,4-triazol-5-ylidene carbene (**1**) in presence of methanol as initiator ($[\mathbf{1}]_0/[MeOH]_0 = 1$) has been conducted at 80 °C for 25 min ($[BL]_0 = 5$ mol L^{-1}; $[BL]_0/[MeOH]_0 = 50$) in different toluene-to-*t*-BuOH cosolvents (*M*) ratios ($1/0 \leq M \leq 0/1$) (Figure 1). Evolutions of final conversions from 50 to 73%, when polymerization is conducted from respectively pure toluene to pure *t*-BuOH, might be explained by the influence of solvent dielectric constant on the rate of propagation for a dipolar molecule-dipolar molecule reaction, arguing an ionic polymerization process.

In comparison to previous results,[6] even though in limited relative amount (with regards to the total end groups quantity) crotonate species proved to be present when polymerizations were conducted in *t*-BuOH/toluene solvent mixture. Such results emphasize the importance of polymerizing BL in anhydrous *t*-BuOH used as the only solvent to get rid of even negligible undesirable crotonate species also able to initiate subsequent propagations leading to the loss of molecular weight and end group fidelity, especially for high targeted polymerization degrees (DPs).

Accordingly, the polymerization of BL with MeOH/**1** was carried out at 80 °C in pure anhydrous *t*-BuOH ($[BL]_0 = 1$ mol L^{-1} and 9.7 mol L^{-1}). Even if some differences are observed for high targeted DPs, molecular weights obtained under these conditions correlated with those predicted with the monomer-to-initiator ratios (taking into account respective conversions), ranging from 50 to 495 and yielded polymers with narrow dispersities (Table 1). Gel permeation chromatography (GPC) traces (Figure S1) of PBL initiated from 1-pyrenemethanol (entry 5, Table 1) using both refractive index and UV detectors (410 and 300 nm, respectively) attested for the distribution of pyrene extremity throughout the sample corroborating the end group fidelity also evidenced by ^1H NMR (not shown here).

Table 1. Selected Polymerization Data of BL When Initiating from Alkoxy Adducts[a]

entry	M/I[c]	time (h)	convn (%)[d]	$M_{n,th}$ (g/mol)[e]	$M_{n,exp}$ (g/mol)[f]	PDI[f]
1	53	16	95	4543	5300	1.22
2	107	27	90	8407	6300	1.30
3	147	54	99	12 400	13100[g]	1.12
4	246	97	97	21 520	20850[g]	1.32
5[b]	990	4.6	50	42 570	34900[g]	1.09

[a] Conditions: $[BL]_0 = 1$ mol L^{-1}, initiator = MeOH/**1** (1/1), 80 °C in *t*-BuOH. [b] Conditions: $[BL]_0 = 9.7$ mol L^{-1}, initiator = 1-pyrenemethanol/**1** (1/1). [c] Monomer-to-initiator ratio. [d] Conversion as determined by ^1H NMR spectroscopy. [e] Theoretical molecular weight. [f] Molecular weight and polydispersity index as determined by gel permeation chromatography. [g] Molecular weight as determined by tonometry.

Interestingly, the end group analysis of the polyester chains revealed the presence of a carboxylic acid end group,[7] meaning that carboxylate were the eventually propagating species of the ROP. To elucidate the nature of the active centers formed at various stages of the polymerization of BL, several model experiments were conducted from the poly(ethylene oxide) α-methyl-*ω*-hydroxyl (PEO−OH) initiator and **1** at 80 °C in *t*-BuOH with targeted DPs ranging from 1 (monomer) to 25.

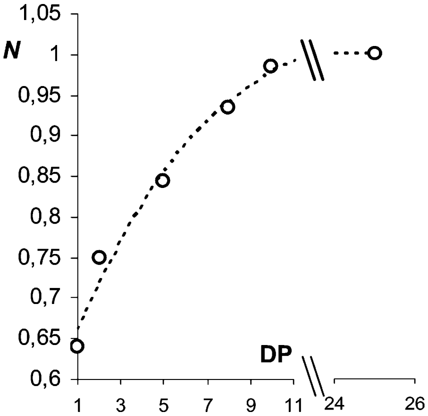


Figure 2. Relationship between the relative number of carboxylic acid end groups per PBL oligomers with respect to the alkoxide ones (*N*) and the correlated DP.

As active growing centers, both alkoxide and carboxylate groups were found at the early stages of the reaction while the relative number of carboxylate end groups increased during the course of polymerization to finally represented the only propagating center for DPs higher than ca. 10 (Figure 2). Such observation has also been confirmed by ^{31}P NMR after polymerizing BL by MeOH/**1** at 80 °C in *t*-BuOH for 9 h ($[\mathrm{BL}]_0 = 5$ mol L^{-1}; DP = 100; $M_{\mathrm{n,GPC}} = 9000$ g mol^{-1}; PDI = 1.11) and quenching the reaction by an excess of diphenyl chlorophosphate. As previously reported by Penczek et al., the spectrum does display the expected shift with $\delta = -28$ ppm, i.e., in the area characteristic for the tetraphenoxy diphosphate resulting from the carboxylate active extremities (Figure S3).[8]

Further evidence of adducts formation from both hydroxyl and carboxylic acid terminated structures with free carbene was provided by an NMR-scale single turnover experiment. A solution of **1**, methanol and BL in dry *t*-BuOH ($[\mathbf{1}]_0 = [\mathrm{MeOH}]_0 = [\mathrm{BL}]_0 = 0.43$ mol L^{-1}) was heated to 80 °C overnight. Upon cooling, the ^{1}H NMR spectrum of the product (recorded in benzene-d_6) revealed that the BL had been completely consumed with product assigned as a carbene adducts mixture of both methyl ester and methyl ether of ring-opened BL. Figure 3 represents the ^{1}H NMR spectrum of the as-obtained mixture of both adducts as well as their corresponding hypothetical molecular structures as drawn in reference to the state of art.[6a,9]

A kinetic study of BL polymerization from MeOH/**1** ($[\mathrm{MeOH}]_0/[\mathbf{1}]_0 = 1/1$) was performed at 80 °C in *t*-BuOH using an initial monomer concentration ($[\mathrm{BL}]_0$) of 1 mol L^{-1} while varying the initial monomer-to-adduct molar ratios ($13 \leq [\mathrm{BL}]_0/[\mathrm{MeOH}/\mathbf{1}]_0 \leq 256$). Albeit kinetic plots in semilogarithmic coordinates exhibit an initial induction period, the linear dependence of $\ln([\mathrm{BL}]_0/[\mathrm{BL}])$ vs time demonstrates that the polymerization of BL is first order with respect to monomer and that the number of growing species does not change appreciably during polymerization (Figure 4). The as-observed induction might be due to coexistence of both alkoxide with carboxylate growing species in the early stage of the polymerization (Figure 2). The slope of the linear relationships corresponds to apparent propagation rate constant (k_{app}) values. The partial order in adduct, *a*, and the absolute rate constant, k_{p}, have then been approximated by assuming that $k_{\mathrm{app}} = k_{\mathrm{p}}[\mathrm{MeOH}/\mathbf{1}]^a$. A linear regression of $\ln(k_{\mathrm{app}})$ vs $\ln[\mathrm{MeOH}/\mathbf{1}]$ results in a k_{p} value of 15.27 L·mol^{-1}·h^{-1} and a partial order in initiator *a* equal to 1.08 (~1) (Figure 5). These results demonstrate that the polymerization is first-order both in monomer and methoxytriazolium adduct concentrations, leading to the following overall rate equation: $\mathrm{d}[\mathrm{BL}]/\mathrm{d}t = 15.27\,[\mathrm{BL}]^1[\mathrm{MeOH}/\mathbf{1}]^1$.

Such kinetics data give credit to our previous observation and point toward an anionic polymerization mechanism initiated by reaction of **1** with methanol to provide alkoxide anions where

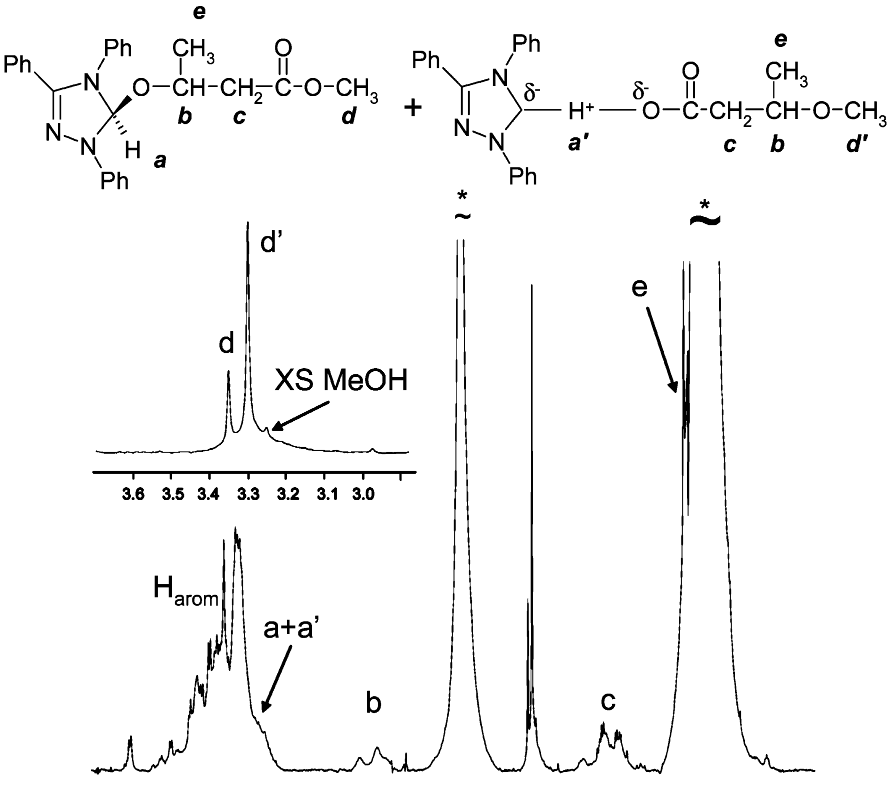


Figure 3. Single-turnover experiment realized between **1**, methanol and BL in *t*-BuOH (*) at 80 °C (NMR recorded in benzene-d_6).

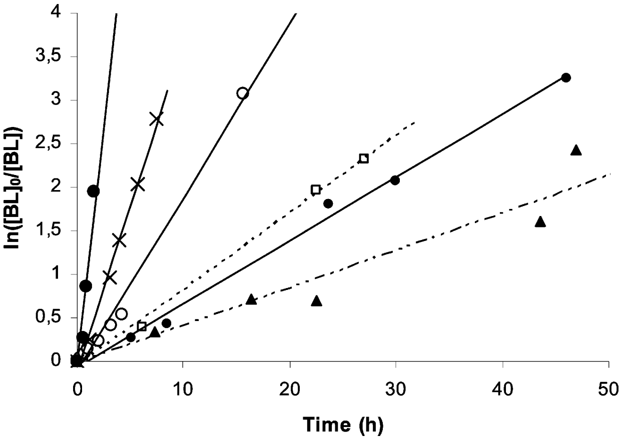


Figure 4. Time dependence of monomer conversion in BL polymerization as initiated with MeOH/**1** in *t*-BuOH at 80 °C for $[\mathrm{BL}]_0$ of 1 mol L^{-1} and various $[\mathrm{BL}]_0/[\mathrm{MeOH}/\mathbf{1}]_0$: (●) 13, (×) 29, (○) 53, (□) 107, (•) 147, and (▲) 256.

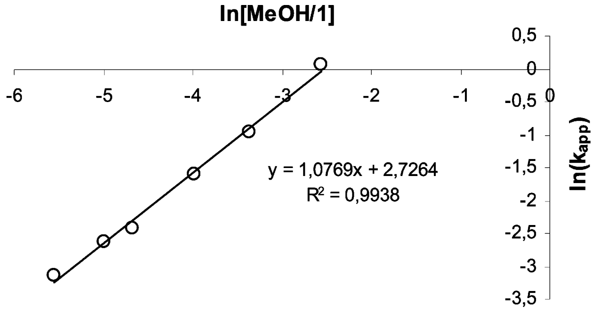


Figure 5. Logarithmic dependence of the apparent rate constant of BL polymerization initiated with MeOH/**1** on the initial adduct concentration in the feed. Conditions of polymerization are given in the caption for Figure 4.

the protonated **1** (**1**-H) plays the role of associated counterion (Scheme 2). These combined data provide other evidence to suggest the formation of both carbene/alcohol and carbene/carboxylic acid adducts confirming both acyl− and alkyl−oxygen cleavages in the early stage of the BL anionic polymerization from an alcohol initiator added with **1** in pure *t*-BuOH at 80 °C. Since alkoxide initiating species produced by deprotonation of alcohol by **1** convert into carboxylate ones after ca. 10 insertion steps, the two different adducts, i.e., alkoxyadduct ($[\mathrm{R{-}OH}]_0/[\mathbf{1}]_0 = 1$) and carboxyadduct ($[\mathrm{R{-}COOH}]_0/[\mathbf{1}]_0 = 1$), should show comparable rate constants for DPs higher than 10. Kinetic experiments were thus performed with BL in *t*-BuOH at 80 °C to compare propagation rate constants for polymerization initiated with carboxyadduct and alkoxyadduct. Two polymerizations were carried out for same targeted DPs (DP = 50 at 100% conversion) with an initial monomer concentration of 1 mol L^{-1} using 1-pyrenemethanol and 1-pyreneacetic acid (both added with 1 equiv of **1**) as alcohol and carboxylic acid initiators, respectively (Figure 6). Values of k_{app} obtained for both initiator adducts are practically equal for processes initiated with either 1-pyrenemethanol/**1** or 1-pyreneacetic acid/**1**. The identity of the measured k_{app} values leads again to the conclusion, that the propagating active species are carboxylate anions irrespective of the initiator used.

Table 2 summarizes molecular characterizations of PBL samples obtained from polymerization of BL with 1-pyreneacetic acid/**1** for various monomer-to-carboxyadduct ratios. The experimental molecular weights ($M_{\mathrm{n,exp}}$) agreed well with the theoretical values ($M_{\mathrm{n,th}}$) while all samples were characterized by a very narrow polydispersity, assuming a “living” process. It is worth noting that such kinetics is much faster than the one reported by Jedlinski when BL is polymerized from tetrabutylammonium salts of carboxylic acids used as initiator. For instance a poly([*R*,*S*]-*β*-butyrolactone) of 31 000 g mol^{-1} was obtained after 300 h of polymerization ($[\mathrm{BL}]_0 = 4$ mol L^{-1}, 25 °C, in $\mathrm{CHCl_3}$).[5a] Moreover, as previously observed for PBL chains as initiated from 1-pyrenemethanol, gel permeation chromatography (GPC) traces (Figure 7) of PBL initiated from 1-pyreneacetic acid (entry 4, Table 2) using both refractive index and UV detectors (410 and 300 nm, respectively) show distribution of pyrene extremities throughout the sample.

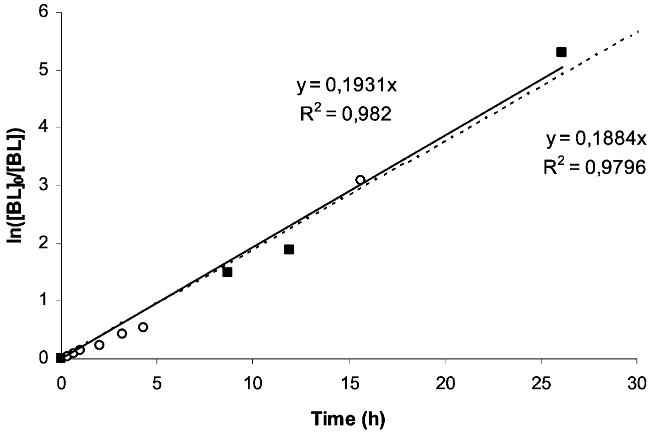


Figure 6. First-order plots for polymerization of BL in *t*-BuOH at 80 °C and initiated with 1-pyrenemethanol/**1** (--○--) and 1-pyreneacetic acid/**1** (■).

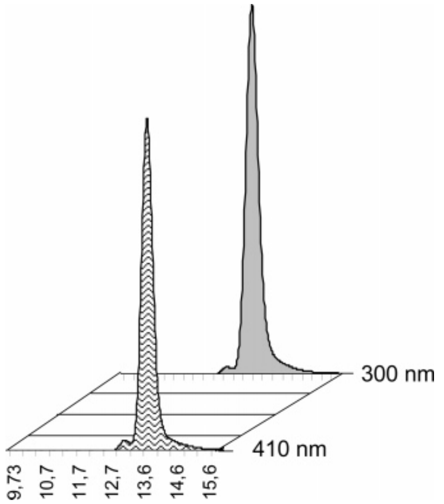


Figure 7. SEC of PBL using a DRI detector (410 nm) and UV detector (300 nm) (entry 4 in Table 2).

Table 2. Selected Polymerization Data of BL as Initiated from Carboxyadducts[a]

entry	M/I[b]	time (h)	convn (%)[c]	$M_{\mathrm{n,th}}$ (g/mol)[d]	$M_{\mathrm{n,exp}}$ (g/mol)[e]	PDI[e]
1	51	1.8	77	3400	3250	1.09
2	51	2.5	85	3722	4050	1.11
3	51	5.5	99	4368	4150	1.13
4	100	9	99	8500	8300	1.09
5	500	19.3	90	39 000	32200[f]	1.15

[a] Conditions: $[\mathrm{BL}]_0 = 5$ mol L^{-1}, initiator = 1-pyreneacetic acid/**1** (1/1), 80 °C in *t*-BuOH. [b] Monomer-to-initiator ratio. [c] Conversion as determined by ^{1}H NMR spectroscopy. [d] Theoretical molecular weight. [e] Molecular weight and polydispersity index as determined by gel permeation chromatography. [f] Molecular weight as determined by vapor pressure osmometry.

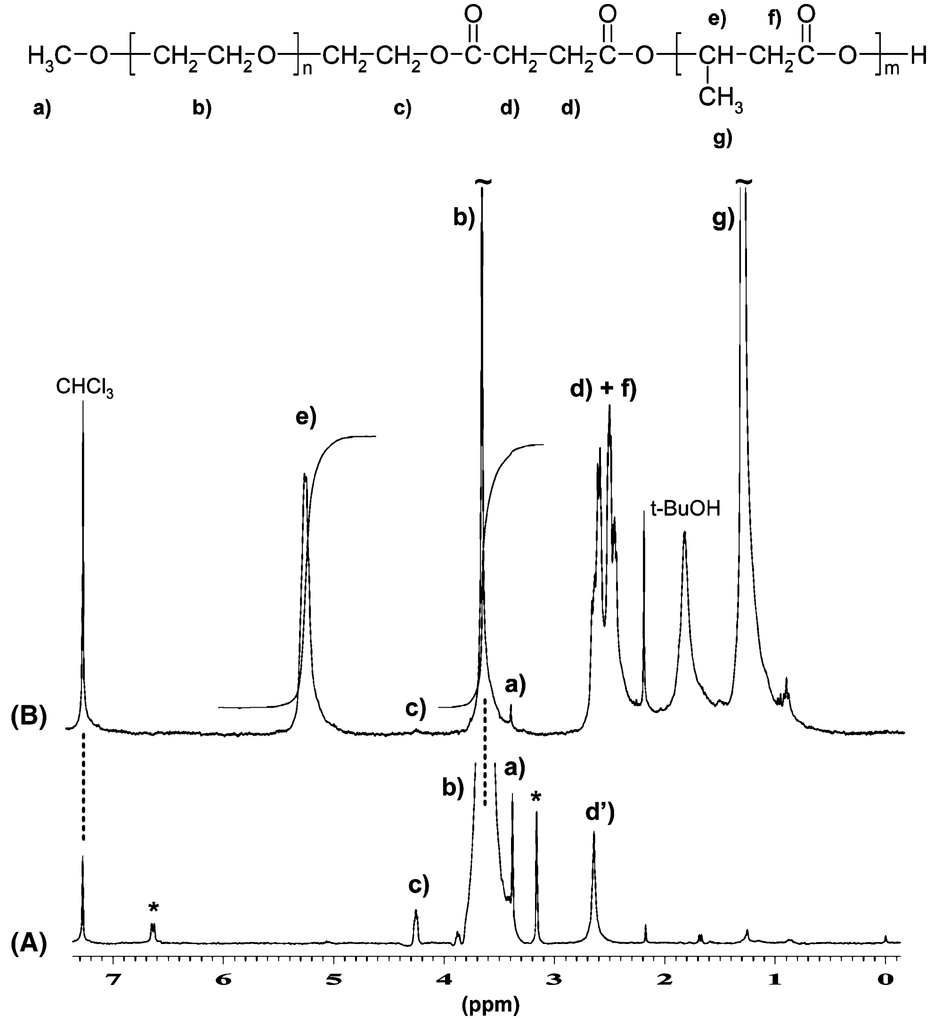
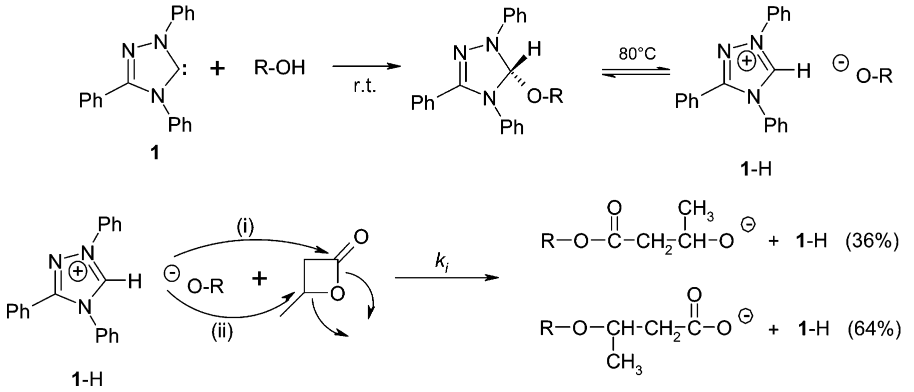


Figure 8. ^{1}H NMR spectra of poly(ethylene oxide), α-methoxy, ω-carboxylic acid (PEO−COOH) ($M_{n,NMR}$ = 2000 g mol^{-1}) (A) and a corresponding poly(ethylene oxide)-*b*-poly([*R*,*S*]-β-butyrolactone) (PEO-*b*-PBL) block copolymer (B) (entry 1, Table 3; (*) DMAP residues, solvent = CDCl$_3$). Reminder: d′ protons correspond to methylene protons d before polymerization of BL.

Scheme 2. Proposed Anionic Initiating Process of BL Polymerization Using Alkoxytriazolium Adduct as Initiator in *t*-BuOH at 80 °C Implying Both "*O*-Acyl" (i) and "*O*-Alkyl" (ii) Cleavages (k_i: Initiating Rate Constant)



Copolymerization from Functionalized Poly(ethylene oxide) Macroinitiator. Adducts of carboxylic acid-functionalized poly(ethylene oxide) were synthesized either in situ or isolated and used as thermally stable macroinitiators for the copolymerization of BL. The preparation of poly(ethylene oxide), α-methoxy, ω-carboxylic acid (PEO−COOH) has been carried out according to Zalipsky et al. by reacting a poly(ethylene oxide) α-methoxy-ω-hydroxyl initiator (PEO−OH) with excess of succinic anhydride for 24 h at room temperature in presence of *N*,*N*-dimethylaminopyridine and triethylamine.[10] ^{1}H NMR spectroscopy attests to the completion of reaction with the intensity ratio between α-methoxy protons (H$_a$) at 3.35 ppm and ω-carboxymethylene ones at 2.65 ppm (H$_d$) being equal to the expected 3/4 ratio (Figure 8A).

The ring-opening polymerization of BL has then been conducted from the as-obtained PEO−COOH ($M_{n,NMR}$ = 2000 g mol^{-1}; PDI = 1.05) at 80 °C in *t*-BuOH for an initial monomer concentration of 5 mol L^{-1} and an initial monomer-to-macroinitiator ratio of 216. Table 3 shows the time dependence of the number-average molecular weight of the PBL block of

Table 3. Time dependence of Experimental Number-average Molecular Weight in PBL ($M_{n,PBL,NMR}$) and Apparent Number-average Molecular Weight of PEO-*b*-PBL Block Copolymers ($M_{n,copo,GPC}$) as Recovered in *t*-BuOH at 80 °C by a PEO−COOH/1 Macroinitiator ($M_{n,PEO} = 2{,}000$ g mol^{-1}; $[\text{PEO−COOH}]_0/^{1}{}_0 = 1$, $[\text{BL}]_0/[\text{PEO−COOH}]_0 = 216$, and $[\text{BL}]_0 = 5$ mol L^{-1})

entry	time (h)	$M_{n,PBL,NMR}$ (g/mol)[a]	$M_{n,copo,GPC}$ (g/mol)[b]	PDI[b]
1	1.9	16 000	8400	1.18
2	3.0	18 600	9200	1.20
3	20.2	20 200	10 500	1.25
4	27.8	19 800	10 400	1.31

[a] As determined by ^{1}H NMR based on the relative intensity of the repetitive units of the PBL block (−C***H***(CH$_3$)−) at 5.25 ppm and the PEO block (−(C***H***$_2$)$_2$−) at 3.6 ppm and taking into account the number-average molecular weight of the PEO macroinitiator. [b] Apparent molecular weight and polydispersity index as determined by gel permeation chromatography in THF at 35 °C.

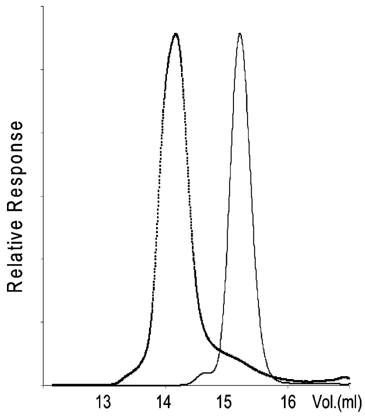


Figure 9. SEC traces of PEO−COOH macroinitiator (right) and its corresponding PEO-*b*-PBL diblock copolymer (left) (entry 3, Table 3).

the as-obtained copolymer samples. Experimental number-average molecular weight in PBL ($M_{n,PBL,NMR}$) was determined by ^{1}H NMR measurements as illustrated in Figure 8B for one selected copolymer sample (entry 1, Table 3). From Figure 8B, the repetitive proton signals of both PBL and PEO block can be readily observed as well as the protons H$_a$ and H$_c$ assigned to the α-methoxy protons and methyleneoxy carbonyl protons present respectively on both extremities of the PEO block. Neither ω-hydroxymethine protons from PBL extremities (appearing at 4.15 ppm) nor crotonic protons (at 5.8 ppm) can be detected. Such observations clearly indicate that the polymerization of BL occurred selectively through the expected anionic mechanism with an endocyclic *O*-alkyl rupture of the monomer as initiated from the carboxylic acid end group of the PEO−COOH macroinitiator and without any backbiting reactions.

Assuming that all PEO−COOH chains promoted the ROP of BL, $M_{n,PBL,NMR}$ was determined from M_n PEO−COOH macroinitiator based on the relative intensity of the repetitive methine protons H$_e$ of the PBL at 5.25 ppm (−C***H***(CH$_3$)−) and the repetitive methylene protons H$_b$ of the PEO sequence at 3.6 ppm (−(C***H***$_2$)$_2$−) (see Table 3). It is stressed out that the low relative intensity of both H$_a$ and H$_c$ protons does not enable to calculate the length of PBL blocks from these signals (particularly for the other copolymers recovered at higher BL conversion). As highlighted by Table 3, polymerization of BL at 80 °C from PEO−COOH macroinitiator proceeded with near quantitative monomer conversion in 20 h to give PEO-*b*-PBL amphiphilic block copolymer composed by a PBL block characterized by a degree of polymerization of 234 (M_n = 20 200 g mol^{-1}). Assuming an inherent experimental error close to 10%, a good agreement thus exists between theoretical and experimental molecular weights. The SEC trace of PEO-*b*-PBL diblock copolymer is shifted to lower retention volume compared to the PEO−COOH used as macroinitiator (Figure 9).

Surface Tension Measurements. Figure 10 shows the semilogarithmic plot of the surface tension (γ) of a given PEO-*b*-PBL diblock copolymer (entry 4, Table 3) vs its concentration in water (expressed in g·L^{-1}). At 25 °C, the surface tension goes down from 72.5 to 49 mN/m, demonstrating the tensioactive properties of this amphiphilic diblock copolymer. The cmc has been determined from the intersection between the tangents drawn from higher concentration portions of the sigmoidal plots[11,12] and calculated as 1.9×10^{-2} g·L^{-1}.

Conclusion

High molecular weight poly(3-hydroxybutyrate) was produced via "living"/controlled ring-opening polymerization (ROP) of β-butyrolactone (BL) from the adduct formed either primary alcohol or carboxylic acid and 1 equiv of a stable carbene, i.e., 1,3,4-triphenyl-4,5-dihydro-1*H*-1,2,4-triazol-5-ylidene carbene **1**. Structural (multinuclear NMR) and kinetics studies gave credit for an anionic polymerization mechanism where the protonated **1** (**1**-H) played the role of associated counterion while *t*-BuOH was considered as the only polymerization solvent at 80 °C. Interestingly, fine tailoring of molecular weight (with M_n as high as 32 000 g·mol^{-1} and narrow molecular weight distribution)

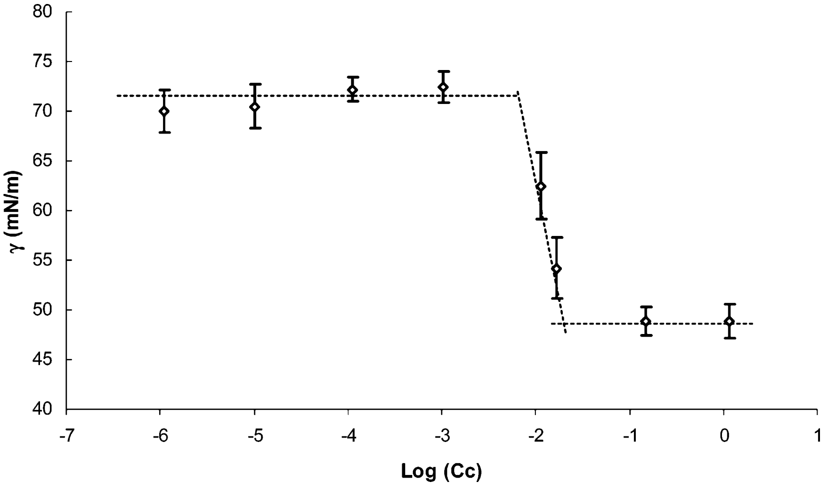


Figure 10. Concentration dependence of the surface tension of the amphiphilic PEO-*b*-PBL diblock copolymer (entry 4, Table 3) in aqueous solution at 25 °C.

could be performed with a perfect control over the nature of the end groups (absence of any crotonation side-reaction). As a result of the achievable control, amphiphilic block copolymers were readily synthesized by polymerization of BL initiated from poly(ethylene oxide) α-methoxy-ω-carboxylic acid allowing again for a fine control over molecular weight and composition. The tensioactivity of the so-obtained copolymer was finally evidenced by preliminary tensiometry experiment, i.e., via the pendant drop method. Undoubtedly this new metal-free anionic ring-opening polymerization of β-lactones will pave the way to novel poly(3-hydroxyalkanoate)-based macromolecular architectures with potential applications in biomedical and pharmaceutical domains.

Experimental Part

General Consideration. [*R*,*S*]-β-Butyrolactone (Acros, 99%) was dried over calcium hydride at room temperature for 48 h and then distilled under reduced pressure. *tert*-BuOH was dried over calcium hydride at 40 °C for 72 h and then distilled under reduced pressure. Toluene (Labscan, 98%) was dried by refluxing over calcium hydride and then distilled prior to use. 1-Pyrenemethanol (ChemLab, 98%) was dried overnight under vacuum at 100 °C. Poly(ethylene oxide), α-methyl, ω-hydroxyl (Fluka, $M_n \sim 2000$) was dried by three azeotropic distillations of toluene, then dried at 60 °C in vacuo overnight. Poly(ethylene oxide), α-methyl, ω-carboxylic acid was synthesized according to literature[8] before being dried by three azeotropic distillations of toluene, then at 60 °C in vacuo overnight. 5-Methoxy-1,3,4-triphenyl-4,5-dihydro-1*H*-1,2-triazol-5-ylidene (Acros, 98%) was purified and degassed at room temperature by three nitrogen/vacuum treatments prior to any polymerization reaction. Trimethylsilyldiazomethane (2 N in hexane from Aldrich), chloro diphenylphosphate (Acros), dimethylaminopyridine (Chem Lab), triethylamine (Chem Lab) and carbone disulfide (Riedel-de Haën, p.a.) were used as received. $CDCl_3$ and benzene-d_6 were purchased from Cortec and used as received. ^1H and ^{31}P NMR spectra were recorded on a 300 MHz spectrometer, with shift reported in parts per million downfield from tetramethylsilane (^1H NMR) or chloro diphenylphosphate (^{31}P NMR) used as internal references. Gel permeation chromatography was performed in tetrahydrofuran on a Waters chromatograph equipped with four 5 μm Waters columns (300 mm × 7.7 mm) connected in series with increasing pore size (10, 100, 1000, 10^5, 10^6 Å). Polystyrene samples of known molecular weight were used as calibration standards. A Waters 410 differential refracometer and 996 photodiode array detector were employed. Number-average molar masses (M_n) were determined in toluene at 45 °C with a vapor pressure osmometer K-7000 (Tonometer) from Knauer. The surface tensions were determined using a Drop Shape Analysis System DSA 10 Mk2 equipped with a thermostated chamber and a Circulator Thermo Haake DC 10.

General Procedure for the Synthesis of Poly([*R*,*S*]-β-butyrolactone) α-Methoxy-ω-carboxylic Acid. In a previously flamed and nitrogen purged round-bottom flask, 50 mg (1.5×10^{-4} mol) of commercially available 5-methoxy-1,3,4-triphenyl-4,5-dihydro-1*H*-1,2-triazol-5-ylidene was purified (from excess of methanol) and degassed at room temperature by three successive nitrogen/vacuum cycles. After treatment, 0.4 mL (4.99 mmol) of [*R*,*S*]-β-butyrolactone and 0.6 mL of *t*-BuOH were then added at room temperature ($[BL]_0 \sim 5$ mol L^{-1}). The polymerization was typically conducted at 80 °C and stopped after 1.25 h by adding a few drops of carbon disulfide (CS_2). The medium is finally poured into 10 volumes of cold pentane (10 mL). The polymer was recovered by filtration and dried under reduced pressure at 50 °C until constant weight, i.e., 0.26 g. Yield: 41%. ^1H NMR (300 MHz, $CDCl_3$, δ, ppm): 0.8−1.4 (d, 3*n*H), 2.1−2.5 (m, 2*n*H), 3.2 (s, 1H), 5.15 (m, *n*H). $M_{n,SEC} = 4{,}150$. $M_w/M_n = 1.19$.

Methylation of Poly([*R*,*S*]-β-butyrolactone) α-Methoxy-ω-carboxylic Acid into Poly([*R*,*S*]-β-butyrolactone) α-Methoxy-ω-methoxyoxycarbonyl. In a previously flamed and nitrogen purged round-bottom flask equipped with a three-way stopcock and a septum, 0.134 g of α-hydroxy-ω-carboxylic acid poly([*R*,*S*]-β-butyrolactone) (3.22×10^{-5} mol, $M_n = 4{,}150$, $M_w/M_n = 1.19$) was dried by three successive azeotropic distillations of toluene (3 × 10 mL). Then, the dried polymer was dissolved in a mixture of 1.3 mL of toluene and 0.15 mL of anhydrous methanol. Nine equivalents of trimethylsilyldiazomethane (2.9×10^{-4} mol, 0.15 mL) compared to the content of carboxylic acid functions was then added. Nitrogen gas evolved through a connected oil valve. After 3 h, the reaction was stopped by the addition of a few drops of acetic acid (0.1 mol L^{-1}) and the volatiles were removed out under reduced pressure. The polymer was recovered by precipitation into 8 volumes of cold pentane (10 mL), filtration and drying under reduced pressure at 50 °C until constant weight, i.e., 0.13 g. Yield = 97%. ^1H NMR (300 MHz, $CDCl_3$, δ, ppm, see Figure S2): 0.8−1.4 (d, 3*n*H), 2.1−2.5 (m, 2*n*H), 3.8 (s, 3H from −C(O)OMe), 5.2 (m, *n*H).

General Procedure for the Synthesis of Poly([*R*,*S*]-β-butyrolactone), α-pyrenemethyloxy-ω-carboxylic Acid. In a previously flamed and nitrogen purged round-bottom flask, 20 mg (8.6×10^{-5} mol) of 1-pyrenemethanol was added with 31 mg (9.4×10^{-5} mol) of 5-methoxy-1,3,4-triphenyl-4,5-dihydro-1*H*-1,2-triazol-5-ylidene. After an overnight under vacuum at 100 °C, the as-obtained green-yellow powder is dissolved in 1 mL of *t*-BuOH before addition of 0.7 mL (8.6 mmol) of [*R*,*S*]-β-butyrolactone at room temperature ($[BL]_0 \sim 5$ mol L^{-1}). After 9 h at 80 °C, the polymerization was stopped by adding a few drops of carbon disulfide (CS_2). The medium was finally poured into 10 volumes of cold pentane (20 mL). The polymer was recovered by filtration and dried under reduced pressure at 50 °C until constant weight, i.e., 0.76 g. Yield: 99%. ^1H NMR (300 MHz, $CDCl_3$, δ, ppm): 0.6−1.3 (d, 3*n*H), 2.0−2.5 (m, 2*n*H), 5.15 (m, *n*H), 7.7−8.4 (m, 9H). $M_{n,SEC} = 9000$. $M_w/M_n = 1.11$.

Note: when the polymerization is stopped by adding few drops of chlorodiphenylphosphate, the following results are obtained: Yield: 98%. ^{31}P NMR (300 MHz, $CDCl_3$, δ, ppm): − 27.79.

General Procedure for the Synthesis of Poly(ethylene oxide)-*block*-poly([*R*,*S*]-β-butyrolactone) from Poly(ethylene oxide) α-Methyl-ω-carboxylic Acid. In a previously flamed and nitrogen purged round-bottom flask, 144 mg (7.2×10^{-5} mol) of poly(ethylene oxide) α-methyl-ω-carboxylic acid ($M_n = 2000$; PDI = 1.05) was added to 24 mg (7.2×10^{-5} mol) of 1,3,4-triphenyl-4,5-dihydro-1*H*-1,2-triazol-5-ylidene pure carbene and solubilized into 3 mL of dried toluene. After an overnight under vacuum at 80 °C, the as-obtained poly(ethylene oxide) α-methyl-ω-ylidene carboxy adduct was dissolved in 1.6 mL of *t*-BuOH before addition of 1.4 mL (16 mmol) of [*R*,*S*]-β-butyrolactone at room temperature ($[BL]_0 \sim 5$ mol L^{-1}). After 28 h at 80 °C, the polymerization was stopped by adding a few drops of carbon disulfide (CS_2). The medium was finally poured into 10 volumes of cold pentane (30 mL). The polymer was recovered by filtration and dried under reduced pressure at 50 °C until constant weight. ^1H NMR (300 MHz, $CDCl_3$, δ, ppm, see Figure 8): 0.9−1.4 (d, 3*m*H), 2.3−2.7 (m, 2*m*H + 2H), 3.4 (s, 3H), 3.5−3.7 (s, 2*n*H), 4.2 (t, 2H), 5.1−5.3 (m, *m*H). $M_{n,SEC} = 10\,400$. $M_w/M_n = 1.31$.

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Supporting Information Available: Figures showing an SEC chromatogram and ^1H NMR analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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