Anionic Ring-Opening Polymerization of a Five-Membered Cyclic Carbonate Having a Glucopyranoside Structure

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ABSTRACT: Anionic ring-opening polymerizations of methyl 4,6-*O*-benzylidene-2,3-*O*-carbonyl-α-D-glucopyranoside (MBCG) were investigated using various anionic polymerization initiators. Polymerizations of the cyclic carbonate readily proceeded by using highly active initiators such as *n*-butyllithium, lithium *tert*-butoxide, sodium *tert*-butoxide, potassium *tert*-butoxide, and 1,8-diazabicyclo[5.4.0]undec-7-ene, whereas it did not proceed by using *N*,*N*-dimethyl-4-aminopyridine and pyridine as initiators. In a polymerization of MBCG (1.0 M), 99% of MBCG was converted within 30 s to give the corresponding polymer with number-averaged molecular weight (M_n) of 16,000. However, the M_n of the polymer decreased to 7500 when the polymerization time was prolonged to 24 h. It is because a backbiting reaction might occur under the polymerization conditions. © 2013 Wiley Periodicals, Inc. J. Polym. Sci., Part A: Polym. Chem. **2013**, *51*, 1651–1655

KEYWORDS: anionic polymerization; five-membered cyclic carbonate; glucopyranoside; polycarbonates; ring-opening polymerization

INTRODUCTION Aromatic polycarbonates, which have high thermal stability and high mechanical strength, are known as one of typical engineering plastics produced industrially in a large scale. On the other hand, aliphatic polycarbonates had been paid less attention in the past because of their lower thermal and mechanical stability compared with the aromatic polycarbonates. In these days, however, the aliphatic polycarbonates are getting more attention because they have good biodegradability and biocompatibility.[1–5] In recent years, ring-opening polymerizations of cyclic carbonates have been widely studied by many researchers to synthesize polycarbonates. Particularly, ring-opening polymerizations of cyclic carbonates with organometals, metal alkoxides, or organobases have become one of the most promising methods to obtain well-defined polycarbonates.[6–16] It is well known that anionic ring-opening polymerizations of six- and seven-membered cyclic carbonates such as cyclotrimethylene carbonates and cyclotetramethylene carbonates easily proceed under mild conditions. However, anionic ring-opening polymerizations of five-membered cyclic carbonates usually require more vigorous conditions with higher temperature, and proceed with an elimination of carbon dioxide to provide polycarbonates containing ether units in the main chain. Therefore, it was considered that polycarbonates solely composed of carbonate repeating units could not be prepared by anionic polymerizations of five-membered cyclic carbonates.

Previously, we have reported in a short communication on the anionic ring-opening polymerization of five-membered cyclic carbonate containing glucopyranoside, methyl 4,6-*O*-benzylidene-2,3-*O*-carbonyl-α-D-glucopyranoside (MBCG).[17] Although MBCG is a five-membered cyclic carbonate, the anionic polymerization of MBCG was induced by potassium *tert*-butoxide (*t*-BuOK) and 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) at below 30 °C, and proceeded without an elimination of carbon dioxide to give the corresponding polycarbonate simply consisted of a carbonate repeating unit. However, details of the anionic polymerization behaviors have been not studied so far.

In this article, we report the effects of polymerization conditions (initiator, solvent, time, and monomer concentration) on the anionic ring-opening polymerization of MBCG (Scheme 1).

EXPERIMENTAL

Materials

Tetrahydrofuran (THF) was distilled over sodium benzophenone ketyl. *N*,*N*-Dimethylformamide (DMF) was distilled over calcium hydride (CaH_2) under reduced pressure. MBCG was prepared from methyl α-D-glucopyranoside, benzaldehyde dimethyl acetal, and ethyl chloroformate according to the literature (Scheme 2).[18,19] Methyl α-D-glucopyranoside was purchased from Sigma-Aldrich (St. Louis, MO) and recrystallized from methanol before use. Benzaldehyde dimethyl acetal was purchased from Sigma-Aldrich. Ethyl chloroformate was purchased from Tokyo Chemical Industry (Tokyo, Japan). *n*-Butyllithium (*n*-BuLi) was purchased from Kanto Kagaku

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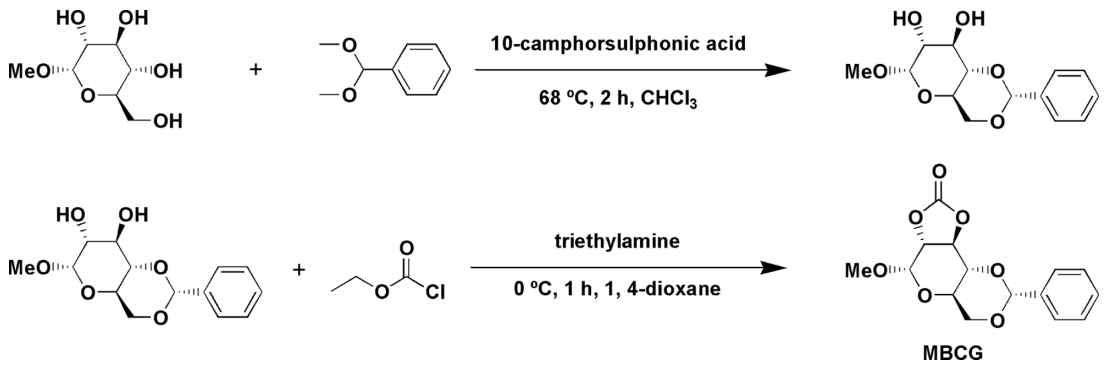
SCHEME 1 Anionic ring-opening polymerization of MBCG.



SCHEME 2 Synthesis of MBCG.

(Tokyo, Japan). Lithium *tert*-butoxide (*t*-BuOLi) in THF solution (1 M) and sodium *tert*-butoxide (*t*-BuONa) in THF solution (2 M) were purchased from Sigma-Aldrich. *t*-BuOK was purchased from Wako Pure Chemical Industry (Osaka, Japan). DBU was purchased from Wako Pure Chemical Industry and distilled over CaH_2 under reduced pressure. *N*,*N*-Dimethyl-4-aminopyridine (DMAP) was purchased from Wako Pure Chemical Industry and recrystallized from *n*-hexane before use. Pyridine was purchased from Wako Pure Chemical Industry and distilled over CaH_2 under reduced pressure.

Measurements

Nuclear magnetic resonance (NMR) measurements were recorded on JEOL JNM ECS 400 in DMSO-d_6 with tetramethylsilane as an internal standard. Number-average molecular weight (M_n) and polydispersity (M_w/M_n) were estimated from size exclusion chromatography performed on a Tosoh chromatograph model HLC-8220GPC equipped with Tosoh TSKgel Super AW 2500 columns (6.0 mm I.D. × 15 cm), TSKgel Super AW 3000 columns (6.0 mm I.D. × 15 cm), and TSKgel Super AW 4000 columns (6.0 mm I.D. × 15 cm), using DMF containing 10 mM lithium bromide as an eluent at the flow rate of 0.5 mL/min at 40 °C. The molecular weight calibration curve was obtained with polystyrene standards.

TABLE 1 Effect of Initiator on Anionic Polymerizations of MBCG[a]

Run	Initiator	Yield[b] (%)	M_n[c]	M_w/M_n[c]
1	*n*-BuLi	98	13,700	1.56
2	*t*-BuOLi	81	5,700	2.62
3	*t*-BuONa	96	12,100	2.18
4	*t*-BuOK	88	8,600	2.02
5	DBU	71	11,000	1.44
6	Pyridine	No polymerization		
7	DMAP	No polymerization		

[a] Polymerization conditions: $[MBCG]_0$ = 3.0 M, $[MBCG]_0/[initiator]_0$ = 25, r.t., 12 h, in THF.
[b] Methanol-insoluble part.
[c] Estimated by GPC analysis (eluent: DMF, polystyrene standards).

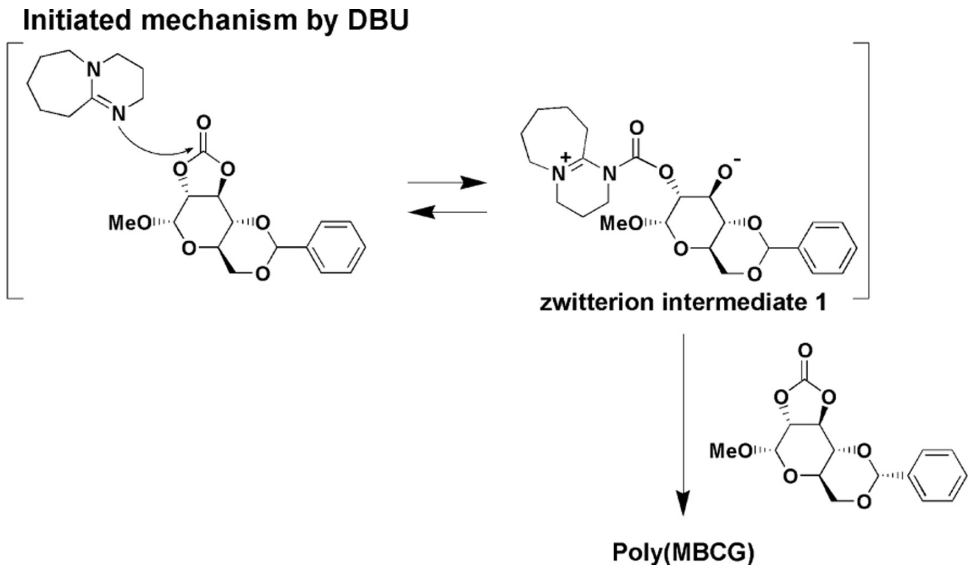
Anionic Ring-Opening Polymerizations of MBCG

A typical polymerization procedure is described below. MBCG (0.308 g, 1.0 mmol) was placed in a Schlenk reaction tube. The flask was evacuated and then filled with nitrogen gas. THF (0.7 mL) was added to the flask under nitrogen atmosphere. *t*-BuONa THF solution (20 μL, 1 M) was added in a stream of nitrogen to initiate polymerization. After the prescribed time, polymerization was terminated with two drops of acetic acid. The polymerization solution was poured into 100 mL of methanol. The resulting precipitate was

TABLE 2 Effect of Monomer Concentration on Anionic Polymerizations of MBCG[a]

Run	Initiator	$[MBCG]_0$ (M)	Yield[b] (%)	M_n[c]	M_w/M_n[c]
1	*n*-BuLi	1.0	89	5,700	1.70
2		0.5	88	5,200	1.62
3	*t*-BuONa	1.0	76	7,800	1.58
4		0.5	77	7,100	1.75
5		0.25	83	7,700	1.81
6	DBU	1.0	43	6,000	1.49
7		0.5	8	3,600	1.24

[a] Polymerization conditions: $[MBCG]_0/[initiator]_0$ = 25, r.t., 12 h, in THF.
[b] Methanol-insoluble part.
[c] Estimated by GPC analysis (eluent: DMF, polystyrene standards).



SCHEME 3 Plausible mechanism of initiation reaction with DBU.

collected by centrifugation and purified by reprecipitation from THF–methanol systems two times. The obtained polymer was dried at 60 °C *in vacuo* to afford 96% yield. The M_n and M_w/M_n were 12,100 g/mol and 2.18, respectively.

^{1}H NMR (DMSO-d_6, 400 MHz): δ = 3.06–3.65 (br, 3H, CH_3), 3.62–4.94 (br, 2H, CH_3—O—CH—C*H*— and CH_3—O—CH—CH—C*H*—), 4.12–4.34 (br, 2H, —CH—C*H*H—O— and —C*H*—CH—CH_2—O—), 4.68–4.78 (br, 1H, —CH—C*H*H—O—), 4.87–5.26 (br, 2H, —C*H*—O—CH_3 and —C*H*—CH—CH_2—O—), 5.47–5.70 (br, 1H, —C*H*—Ph), and 7.03–7.49 (br, 5H, Ph). ^{13}C NMR (DMSO-d_6, 400 MHz): δ = 56.0 (CH_3), 62.6 (—*C*H—CH_2—), 68.1 (—*C*H_2—O—), 74.4 (O=C—O—*C*H—*C*H—O—C=O), 77.9 (—*C*H—CH—CH_2—), 97.0 (—*C*H—O—CH_3), 100.8 (—*C*H—Ph), 126.3 (Ar), 128.8 (Ar), 129.6 (Ar), 137.0 (Ar), and 153.8 (C=O).

RESULTS AND DISCUSSION

Anionic Polymerization of MBCG with Various Initiators

In the previous work, the anionic polymerizations of MBCG were carried out with *t*-BuOK and DBU in 3 M monomer solution.[17] To evaluate the effect of an initiator in detail, we examined the anionic polymerization with various initiators such as *n*-BuLi, *t*-BuOLi, *t*-BuONa, *t*-BuOK, DBU, DMAP, and pyridine at room temperature for 12 h in THF (3 M). The conditions and results are summarized in Table 1. Using *n*-BuLi, *t*-BuOLi, *t*-BuONa, *t*-BuOK, and DBU as initiators, the anionic polymerization smoothly proceeded to obtain the corresponding poly(MBCG)s in 71–98% yield. The number-averaged molecular weights (M_ns) were in a range from 5700 to 13,700. The dispersities of the obtained polymers (M_w/M_n = 1.44–2.62) were broader than we expected. The broader dispersity may be due to an occurrence of backbiting reaction. This will be discussed later. On the other hand, the anionic polymerizations of MBCG initiated with DMAP and pyridine did not proceed and resulted in the quantitative recovery of the monomer. This is presumably because the nucleophilicity of DMAP or pyridine is lower than that of *n*-BuLi, *t*-BuOLi, *t*-BuONa, *t*-BuOK, and DBU. These results suggest that the reactivity of the five-membered cyclic carbonate (MBCG) toward ring opening might strongly depend on the nucleophilicity of the initiator.

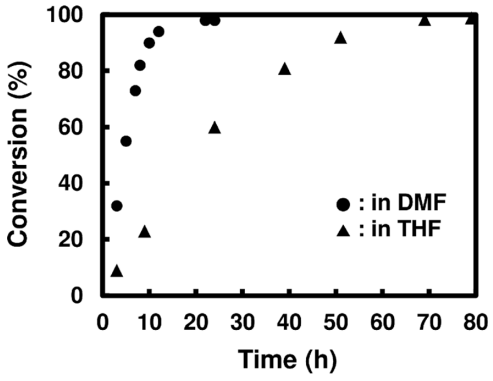


FIGURE 1 Time dependence of the polymerization of MBCG in THF and DMF.

Anionic Polymerization of MBCG at Various Monomer Concentrations

We examined the effect of monomer concentration on the polymerization behavior. The polymerizations were carried

TABLE 3 Anionic Polymerizations of MBCG with *t*-BuONa[a]

Run	$[MBCG]_0/[Initiator]_0$	Yield[b] (%)	$M_{n\ theo}$[c]	M_n[d]	M_w/M_n[d]
1	50	86	15,260	12,700	1.99
2	100	89	30,210	18,100	2.08
3	200	89	57,960	20,200	1.82

[a] Polymerization conditions: $[monomer]_0$ = 0.25 M, r.t., 2 h, in THF.
[b] Methanol-insoluble part.
[c] $M_{n\ theo}$ = (molecular weight of MBCG) × ($[MBCG]_0/[initiator]_0$) × (conversion of MBCG).
[d] Estimated by GPC analysis (eluent: DMF, polystyrene standards).

TABLE 4 Time Dependence of M_n of Poly(MBCG)[a]

Run	$[MBCG]_0$ (M)	Time	M_n[b]	M_w/M_n[b]
1	1.0	30 s	16,000	1.99
2		20 min	11,700	2.08
3		1 h	10,300	1.82
4[c]		12 h	7,800	1.58
5		24 h	6,400	1.71
6	0.25	30 s	8,300	1.85
7		20 min	7,700	1.79
8		1 h	7,700	1.75
9[d]		12 h	7,700	1.81
10		24 h	7,500	1.78

[a] Polymerization conditions: $[MBCG]_0/[initiator]_0 = 25$, r.t., in THF.
[b] Estimated by GPC analysis (eluent: DMF, polystyrene standards).
[c] Run 3 in Table 2.
[d] Run 5 in Table 2.

out with *n*-BuLi, *t*-BuONa, and DBU as initiators at room temperature for 12 h in THF. As shown in Table 2, by using *n*-BuLi and *t*-BuONa, the polymers with moderate M_ns of 5200–7800 were obtained in high yield (76–89%). In these cases, yield and molecular weight of the obtained polymers did not depend much on the monomer concentrations. In particular, the polymerization initiated with *t*-BuONa proceeded even in 0.25 M solution to obtain the corresponding poly(MBCG) in 83% yield. The polymerization activity of *n*-BuLi and *t*-BuONa was the highest in our results. On the other hand, the yield and M_n of the polymer obtained by DBU decreased as the monomer concentration decreased. This implies that the polymerization mechanism initiated with DBU may be different from those initiated with *n*-BuLi and *t*-BuONa. In the DBU-induced anionic polymerization of the cyclic carbonate, a zwitterion intermediate **1** was formed by a nucleophilic addition of DBU to the cyclic carbonate as the initiation step (Scheme 3). However, the reaction is in equilibrium and regenerates the monomer and the initiator. Therefore, the polymerization behavior may be highly susceptible to the monomer and initiator concentrations. As a result, the polymer yield and M_n widely varied with the concentrations in the polymerization using DBU as an initiator.

Anionic Polymerization of MBCG with DBU

Figure 1 shows the time conversion of MBCG initiated with DBU in DMF and in THF. Using DMF as a solvent, the polymerization of MBCG proceeded rapidly and MBCG was consumed within 24 h. In contrast, it took 72 h that the monomer was quantitatively consumed in the polymerization in THF. We consider that this marked difference in the polymerization rates is due to the difference in the reactivities of the polymer chain ends. The anionic polymer chain end was more activated in DMF than in THF. Comparing with the molecular weights of the polymers, the polymer obtained in DMF had lower molecular weight (M_n = 4800) than that of the polymer obtained in THF (M_n = 11,400). This is presumably because chain transfer including backbiting occurred more frequently in DMF than in THF.

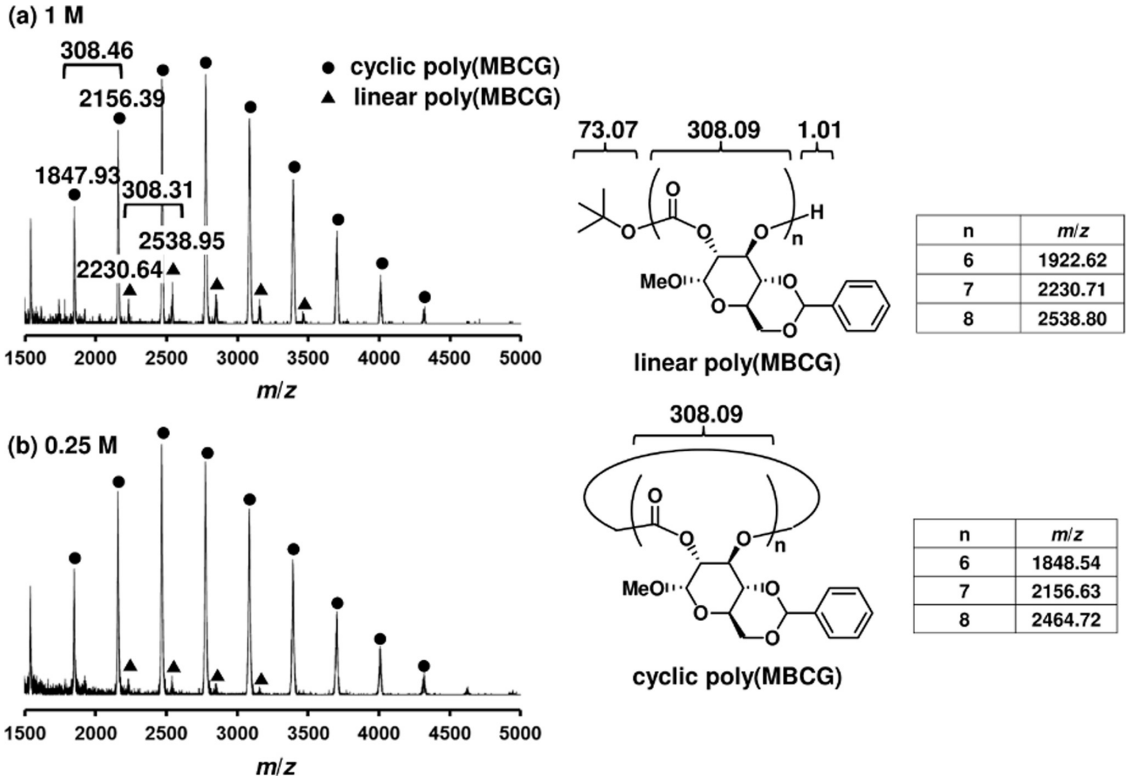


FIGURE 2 MALDI-TOF MS spectra of poly(MBCG) obtained with *t*-BuONa.

Anionic Polymerization of MBCG with *t*-BuONa

As mentioned above, the polymerization of MBCG with *t*-BuONa gave the corresponding polymer in high yield as shown in Table 2. Then, we examined the effect of initiator amount on the polymerization in detail under this polymerization condition (Table 3). In all $[MBCG]_0/[initiator]_0$ ratios examined here ranging from 50 to 200, poly(MBCG) could be obtained in high yield. In particular, the condition of run 3 ($[MBCG]_0/[initiator]_0 = 200$) gave the polymer in 89% yield, whose molecular weight was the highest ($M_n = 20{,}200$). It is worth nothing that the M_ns were always lower than the $M_{n\,theo}$. This is presumably because backbiting reaction occurred during the polymerization. To further examine the polymerization, we checked time-evolved polymerization behavior using *t*-BuONa as an initiator. Table 4 shows the results of the polymerization with *t*-BuONa at room temperature in THF. In the case of 1 M solution, MBCG was quantitatively consumed within 30 s. Thus, the polymerization rate with *t*-BuONa was much faster than that with DBU (Table 2, run 6). The number-averaged molecular weight of the polymer obtained at 30 s was 16,000. However, the molecular weight decreased to 6400 when the polymerization time was prolonged to 24 h. Hence, the backbiting reaction might occur from a growing alkoxide chain end to carbonate group in the same polymer chain. The polymerization smoothly proceeded even in more diluted solution (0.25 M) to give a polymer in 93% conversion for 30 s. In this case, however, the molecular weight of the polymer was almost constant as the polymerization time evolved. Thus, it was assumed that backbiting reaction tends to take place more frequently in the concentrated polymerization condition. To check the structures of the obtained polymers in detail, we carried out MALDI-TOF MS measurements. Figure 2 shows the MALDI-TOF MS spectra of the polymers obtained in 1.0 and 0.25 M solutions. In the spectra of Figure 2(a), two series of signals (● and ▲) were observed. Both series had the same peak intervals of 308 m/z corresponding to the molecular weight of the monomer repeating unit. Judging from their signal positions, these spectra are assigned to be a linear structure (▲) and a cyclic structure (●) formed by backbiting reaction, respectively. The signals of a cyclic structure were observed even in the polymer obtained in 0.25 M solution [Fig. 2(b)], though the molecular weight did not decrease. Thus, in both concentrations, the obtained polymers contained cyclic structure, which were formed by backbiting reaction. It suggests that the backbiting reaction might be inevitable in the polymerization of MBCG under the present conditions.

SUMMARY

We investigated on the anionic ring-opening polymerization of MBCG in detail under various conditions. The polymerizations initiated with *n*-BuLi, *t*-BuOLi, *t*-BuONa, *t*-BuOK, and DBU smoothly proceeded to give the corresponding polymers. Presumably, this may be caused by the ring strain of carbonate ring connected to a bicyclic structure of glucopyranoside. Using DBU as an initiator, the polymerization rate in DMF was faster than that in THF. It was supposed that the zwitterion intermediate **1** was more favorably formed between MBCG and DBU in DMF than in THF, which was solvated and stabilized by DMF. When the polymerization was performed with *t*-BuONa in 1 M solution, the molecular weight of the polymer decreased as time progressed. MALDI-TOF MS analysis of the obtained polymer revealed that cyclic polymers were produced by a backbiting reaction. We expect that the polycarbonate having glucopyranoside structure synthesized here can be a novel biocompatible or biodegradable material in the future.

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