# Synthesis and Anionic Ring-Opening Polymerization Behavior of Amino Acid-Derived Cyclic Carbonates

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ABSTRACT: Synthesis and anionic ring-opening polymerization of L-serine (Ser)- and L-threonine (Thr)-based cyclic carbonates, (2-oxo[1,3]dioxan-5-yl)carbamic acid benzyl ester (Z-S-CC), (4-methyl-2-oxo[1,3]-dioxan-5-yl)carbamic acid benzyl ester (Z-T-CC), and (4-methyl-2-oxo[1,3]dioxan-5-yl)carbamic acid *tert*-butyl ester (Boc-T-CC), were examined. The monomers were synthesized by reaction of triphosgene with the corresponding diols obtained by reduction of *N*-benzyloxycarbonyl-L-serine (Z-Ser), *N*-benzyloxycarbonyl-L-threonine (Z-Thr), and *N*-*tert*-butoxycarbonyl-L-threonine (Boc-Thr). Their ring-opening polymerizations were carried out with *tert*-BuOK, *tert*-BuOLi, and *n*-BuLi as initiators (2−10 mol %) in tetrahydrofuran (THF) at −78 to −30 °C for 1 h to obtain the corresponding polycarbonates. Poly(Z-T-CC) and poly(Boc-T-CC) showed inverted specific rotations with respective to the monomers. The small increase of the absolute values suggested the absence of higher-order structures. The polymers showed three different diads in the ratio of 1:8:1, which agreed well with the value expected from the equimolar reaction of the monomer with *tert*-BuOK. The polymers underwent cleavage of the Z and Boc groups by hydrogenation and acid treatment, respectively to afford the corresponding polycarbonates with free amino groups.

## Introduction

Cyclic carbonates efficiently undergo ring-opening polymerization to yield the corresponding linear polycarbonates under anionic conditions. Höcker et al. have reported anionic polymerization of cyclic carbonates with a variety of functional groups.[1] Cyclic carbonates with bulky substituents undergo anionic equilibrium polymerization.[2] Under cationic conditions, the polymerization is commonly accompanied by partial elimination of carbon dioxide to afford linear polycarbonates containing an ether unit.[3] Kricheldorf et al. have recently reported that tin tetraiodide[4] and butyltin chlorides[5] polymerize a six-membered cyclic carbonate to afford a high molecular weight polycarbonate without accompanying decarboxylation. We have also reported that alkyl halide initiators are effective to suppress the decarboxylation to yield ether unit-free polycarbonates.[6] Cyclic carbonates are expected as filling and adhesive materials, because they show volume expansion during polymerization.[7] This volume expansion can be accounted for by the difference in strength of intermolecular interaction between monomers and polymers. That is, strong interaction in the monomers and weak interaction in the polymers eventually cause the volume expansion. Takeuchi et al. have synthesized ultrahigh molecular weight bisphenol A-based polycarbonate ($M_w$ > 2 000 000) by solid-state ring-opening polymerization of macrocyclic carbonates.[8] The obtained polycarbonate is expected as an engineering plastic with high impact resistance and thermal stability. The other possible use of cyclic carbonate-based polycarbonates is the application to biocompatible and biodegradable materials.[9] If amino acids are employed as starting materials of cyclic carbonates, it would be expected to develop novel optically active polycarbonates applicable to biocompatible materials, because amino acids are components of peptides, indispensable compounds for life process. Recent remarkable advances in fermentation and chemical synthetic methods have enabled us to obtain amino acids with high optical purity and low price. As a result, amino acids and some oligopeptides are now widely used for drugs, foods, and chiral sources in organic synthesis.[10] This article deals with synthesis and anionic polymerization behavior of novel Ser- and Thr-based cyclic carbonates.

## Experimental Section

**Measurements.** $^1$H and $^{13}$C spectra were measured on a JEOL EX-400 spectrometer using tetramethylsilane as an internal standard in $CDCl_3$. Specific rotations were measured by a JASCO digital polarimeter DIP-1000 using a sodium lamp as a light source. Number- and weight-average molecular weights ($M_n$ and $M_w$) and polydispersity indices ($M_w/M_n$) were estimated by gel permeation chromatography (GPC) on a Tosoh HLC-8020 system equipped with four polystyrene gel columns (TSK gels G6000H, G5000H, G4000H, and G2500H), using a 5.8 mM lithium bromide solution in *N*,*N*-dimethylformamide (DMF) as eluent at a flow rate of 1.0 mL/min, polystyrene calibration, and refractive index (RI) and ultraviolet (UV) detectors.

**Materials.** *tert*-BuOK, *tert*-BuOLi (1 mol/L solution in THF each), and *n*-BuLi (1 mol/L solution in *n*-hexane) were used as received. THF was freshly distilled over sodium metal under nitrogen atmosphere before use. Z-serinol, Z-threoninol, and Boc-threoninol were prepared by the reduction of Z-Ser, Z-Thr, and Boc-Thr.[11]

**Synthesis of (2-Oxo[1,3]dioxan-5-yl)carbamic Acid Benzyl Ester (Z-S-CC).** To a solution of Z-serinol (15 g, 170 mmol) and 2,3-dimethyl-1-phenyl-3-pyrazolin-5-one (62 g, 330 mmol) in chloroform (772 mL) was added a solution of triphosgene (16.8 g, 56 mmol) in chloroform (90 mL) at 45 °C, and the resulting mixture was stirred at room temperature overnight. The reaction mixture was washed with 1 M hydrochloric acid (300 mL) twice and then with saturated aqueous NaCl solution

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(300 mL). The organic phase was separated and dried over anhydrous $MgSO_4$ and then filtered. The filtrate was concentrated by rotary evaporation. The residual solid was purified by silica gel column chromatography using *n*-hexane/ethyl acetate (volume ratio 1:1) as eluent and recrystallization from chloroform/ether/*n*-hexane to obtain the product. Yield 74%, mp 142 °C. Anal. Calcd for $C_{12}H_{13}NO_5$ C: 57.37, H: 5.21, N: 5.58. Found C: 57.21, H: 5.28, N: 5.57. $^1H$ NMR $\delta$ ($CDCl_3$): 4.17 (s, 1 H, $-CH-$), 4.44−4.46 (m, 4 H, $-CH(CH_2-)_2$), 5.12 (s, 2 H, $C_6H_5CH_2-$), 6.01 (s, 1 H, $-NH-$), 7.27−7.34 (m, 5 H, $C_6H_5-$) ppm. $^{13}C$ NMR $\delta$ ($CDCl_3$): 42.8 ($\rangle CH-$), 67.3 ($-CH_2-O-$), 70.1 ($-CH\langle(CH_2-)_2$), 128,1, 128.4, 128.6, 135.9 ($C_6H_5-$), 147.8 ($-O-CO-O-$), 156.0 ($-CO-NH-$) ppm. IR (NaCl): 3306, 1900, 1747 ($\rangle C{=}O$), 1698 ($\rangle C{=}O$), 1541, 1242, 1124, 750, 700 $cm^{-1}$.

**Synthesis of (4-Methyl-2-oxo[1,3]dioxan-5-yl)carbamic Acid Benzyl Ester (Z-T-CC).** The title compound was synthesized from Z-threoninol in a similar manner as Z-S-CC. Yield 77%, mp 141 °C. Anal. Calcd for $C_{13}H_{15}NO_5$ C: 58.86, H: 5.70, N: 5.28. Found C: 58.77, H: 5.76, N: 5.29. $^1H$ NMR $\delta$ ($CDCl_3$): 1.38 (d, $J = 6.4$ Hz, 3 H, $-CH_3$), 4.16−4.75 (m, 4 H), 5.14 (s, 2 H, $C_6H_5CH_2-$), 5.62 (s, 1 H, $-NH-$), 7.26−7.37 (m, 5 H, $C_6H_5-$) ppm. $^{13}C$ NMR $\delta$ ($CDCl_3$): 16.9 ($-CH_3$), 46.1 ($-NH-CH\langle$), 67.5 ($-CH_2-O-$), 72.2 ($\rangle CH-CH_3$), 128.1, 128.4, 128.6, 135.8 ($C_6H_5-$), 147.8 ($-O-CO-O-$), 156.3 ($-CO-NH-$) ppm. IR (NaCl): 3304, 1958, 1753 ($\rangle C{=}O$), 1718 ($\rangle C{=}O$), 1537, 1248, 1119, 754, 698 $cm^{-1}$. $[\alpha]_D^{25} = -21.2°$ ($c = 1.00$, $CHCl_3$).

**Synthesis of (4-Methyl-2-oxo[1,3]dioxan-5-yl)carbamic Acid *tert*-Butyl Ester (Boc-T-CC).** The title compound was synthesized from Boc-threoninol in a similar manner as Z-S-CC. Yield 73%, mp 199 °C (dec). Anal. Calcd for $C_{10}H_{17}NO_5$ C: 51.94, H: 7.41, N: 6.06. Found C: 52.10, H: 7.38, N: 6.06. $^1H$ NMR $\delta$ ($CDCl_3$): 1.40 (d, $J = 6.4$ Hz, 3 H, $-CH_3$), 1.47 (s, 9 H, $-C(CH_3)_3$), 4.10−4.77 (m, 4 H), 5.27 (d, $J = 8.8$ Hz, 1 H, $-NH-$) ppm. $^{13}C$ NMR $\delta$ ($CDCl_3$): 16.9 ($\rangle CH-CH_3$), 28.2 ($-C(CH_3)_3$), 45.6 ($-NH-CH\langle$), 72.4 ($\rangle CH-CH_3$), 80.7 ($-C(CH_3)_3$), 148.0 ($-O-CO-O-$), 155.6 ($-CO-NH-$) ppm. IR (NaCl): 3327, 2976, 2932, 1744 ($\rangle C{=}O$), 1709 ($\rangle C{=}O$), 1537, 1250, 1227, 1173, 1117, 770 $cm^{-1}$. $[\alpha]_D^{25} = -17.3°$ ($c = 1.00$, $CHCl_3$).

**Anionic Polymerization.** *Typical procedure*: To a solution of a monomer (1 mmol) in dry THF (5 mL) was added a 1 M solution of *tert*-BuOK in THF (20 mL) at a set temperature under nitrogen, and the reaction mixture was stirred for 1 h. After that, the reaction was quenched by the addition of 1 M HCl in methanol. The monomer conversion was estimated by GPC measurement of the crude polymerization mixture. Then the reaction mixture was poured into ether (200 mL) to precipitate the polymer. It was separated by filtration and dried at 45 °C for 12 h in vacuo. Analytical and spectroscopic data of the obtained polymers are as follows. Poly(Z-S-CC): Anal. Calcd for $C_{12}H_{13}NO_5$. C: 57.52, H: 5.54, N: 5.24. Found C: 57.21, H: 5.28, N: 5.57. $^1H$ NMR $\delta$ ($CDCl_3$): 4.11−1.23 (br, 5H), 5.12 (s, 2 H, $-CH_2-O-$), 5.59−5.84 (br, 1 H), 7.20−7.51 (m, 5 H) ppm. $^{13}C$ NMR $\delta$ ($CDCl_3$): 48.8 ($-NH-CH\langle$), 66.6 ($C_6H_5CH_2-$), 67.1 ($-CH_2-$), 128.2, 128.2, 128.5, 136.0 ($C_6H_5-$), 154.5 ($-O-CO-O-$), 156.1 ($-CO-NH-$) ppm. IR (NaCl): 3326, 2963, 1753($\rangle C{=}O$), 1718 ($\rangle C{=}O$), 1535, 1456, 1404, 1236, 1071, 735 $cm^{-1}$. Poly(Z-T-CC): Anal. Calcd for $C_{13}H_{15}NO_5$. C: 58.87, H: 5.85, N: 5.08. Found C: 58.77, H: 5.76, N: 5.29. $^1H$ NMR $\delta$ ($CDCl_3$): 1.27 (d, $J = 6.4$ Hz, 3 H, $-CH_3$), 4.16−4.74 (m, 4 H), 5.13 (s, 2 H, $C_6H_5CH_2-$), 5.76 (s, 1 H, $-NH-$), 7.26−7.36 (m, 5 H, $C_6H_5-$) ppm. $^{13}C$ NMR $\delta$ ($CDCl_3$): 16.8 ($-CH_3$), 53.0 ($-NH-CH\langle$), 67.2 ($-CH_2-O-$), 73.4 ($\rangle CH-CH_3$), 128.1, 128.2, 128.5, 136.1 ($C_6H_5-$), 153.9 ($-O-CO-O-$), 156.3 ($-CO-NH-$) ppm. IR (NaCl): 3310, 3065, 2988, 2366, 1751 ($\rangle C{=}O$), 1718 ($\rangle C{=}O$), 1537, 1248, 1121, 737, 698 $cm^{-1}$. Poly(Boc-T-CC): Anal. Calcd for $C_{10}H_{17}NO_5$. C: 51.30, H: 7.17, N: 6.14. Found C: 51.10, H: 7.38, N: 6.06. $^1H$ NMR $\delta$ ($CDCl_3$): 1.27−1.56 (m, 12H), 4.00−4.22 (br, 3 H), 4.80−5.05 (m, 2 H) ppm. $^{13}C$ NMR $\delta$ ($CDCl_3$): 16.8 ($\rangle CH-CH_3$), 28.3 ($-C(CH_3)_3$), 52.3 ($-NH-CH-$), 66.4 ($-CH_2-O-$), 73.1 ($\rangle CH-CH_3$), 80.0 ($-C(CH_3)_3$), 154.0 ($-O-CO-O-$), 155.7 ($-CO-NH-$) ppm. IR (NaCl): 3327, 2980, 2935, 1750 ($\rangle C{=}O$), 1709 ($\rangle C{=}O$), 1529, 1248, 1171, 1117, 759 $cm^{-1}$.

**Equimolar Reaction of Boc-T-CC with *tert*-BuOK.** To a solution of Boc-T-CC (231 mg, 1 mmol) in dry THF (3 mL) was added a 0.33 M *tert*-BuOK solution in THF (3 mL) at −78 °C under nitrogen, and the resulting mixture was stirred for 30 min. Prior to the addition, the both solutions were cooled at −78 °C. The reaction was quenched by the addition of 1 M HCl in methanol. The resulting mixture was filtered, and the filtrate was concentrated by rotary evaporation. The residue was purified by preparative TLC eluted with a mixed solvent of ethyl acetate/*n*-hexane (volume ratio 2:1). Yield 90%. $^1H$ NMR $\delta$ ($CDCl_3$): 1.22−1.61 (m, 12H, $-C(CH_3)_3$, $-CH_3$), 3.67 (q, $J = 4.5$ Hz, 1 H × $^8/_9$, $\rangle CHOH$), 3.79 (d, $J = 3$ Hz, 2 H × $^1/_9$, $-CH_2OH$), 4.03 (q, $J = 5.5$ Hz, 2 H × $^8/_9$, $-CH_2O-$), 4.15 (q, $J = 5.5$ Hz, 2 H × $^1/_9$, $-CH_2O-$), 4.43−4.48 (m, 1 H × $^8/_9$, $\rangle CHNH-$), 4.68−4.70 (m, 1 H × $^1/_9$, $\rangle CHNH-$), 5.91 (s, 1 H × $^8/_9$, $-NH-$), 6.12 (s, 1 H × $^1/_9$, $-NH-$) ppm. $^{13}C$ NMR $\delta$ ($CDCl_3$): 15.3 ($\rangle CH-CH_3$ × $^1/_9$), 20.3 ($\rangle CH-CH_3$ × $^8/_9$), 27.6 ($-OCO-OC(CH_3)_3$, $-NHCO-OC(CH_3)_3$ × $^8/_9$), 28.2 ($-NHCO-OC(CH_3)_3$ × $^1/_9$), 55.3 ($-NH-CH\langle$ × $^1/_9$), 57.9 ($-NH-CH\langle$ × $^8/_9$), 66.0 ($-CH_2-O-$ × $^1/_9$), 66.9 ($-CH_2-O-$ × $^8/_9$), 73.8 ($\rangle CH-CH_3$ × $^1/_9$), 76.7 ($\rangle CH-CH_3$ × $^8/_9$), 80.0 ($-C(CH_3)_3$), 153.0 ($-O-CO-O-$), 158.5 ($-CO-NH-$) ppm. IR (NaCl): 3306, 2982, 2935, 1743 ($\rangle C{=}O$), 1456, 1397, 1372, 1280, 1161, 1105, 1059, 990, 860 $cm^{-1}$.

**Hydrogenation of Poly(Z-S-CC).** A suspension of poly(Z-S-CC) (251 mg, 1 mmol as a repeating unit), 5% Pd/C (100 mg), DMF (5 mL), and acetic acid (300 mg, 5 mmol) was stirred at room temperature for 24 h under hydrogen using a balloon. The reaction mixture was filtered through a membrane with 0.5 mm pore size. The filtrate was poured into ether (200 mL) to precipitate the polymer as the acetate. It was separated by filtration and dried at 45 °C for 12 h in vacuo. Yield 95%. $^1H$ NMR $\delta$ (DMSO-$d_6$): 3.54−3.39 (br, 3 H), 3.80−4.10 (br, 4 H), 4.30−5.10 (br, 5 H) ppm. $^{13}C$ NMR $\delta$ (DMSO-$d_6$): 50.1 ($\rangle CH-$), 51.7 ($CH_3-$), 66.3 ($-CH(CH_2-)_2$), 155.8 ($-O-CO-O-$), 158.6 ($CH_3-CO-$) ppm.

**Reaction of Poly(Boc-T-CC) with Trifluoroacetic Acid.** To a solution of poly(Boc-T-CC) (463 mg, 2 mmol as a repeating unit) in $CH_2Cl_2$ (5 mL) was added trifluoroacetitc acid (2.28 g, 20 mmol) in an ice bath, and the resulting mixture was stirred at room temperature for 24 h. The reaction mixture was poured into ether (200 mL) to precipitate the polymer as the trifluoroacetate. It was separated by filtration and dried at 45 °C for 12 h in vacuo. Yield 80%. $^1H$ NMR $\delta$ (DMSO-$d_6$): 1.40 (s, 3H, $-CH_3$), 4.21−4.37 (m, 2 H, $-CH_2-$), 4.50−4.54 (m, 1 H, $CH_3-CH\langle$), 4.97 (s, 1 H, $-CH_2-CH\langle$) ppm. $^{13}C$ NMR $\delta$ (DMSO-$d_6$): 16.1 ($-CH_3$), 52.3 ($-NH-CH-$), 64.7 ($-O-CH_2-$), 72.6 ($\rangle CH-CH_3$), 153.0 ($-O-CO-O-$), 158.8 ($CF_3CO-$) ppm. IR (KBr): 3441, 1763, 1678 ($\langle C{=}O$), 1545, 1253, 1203, 1136, 839, 785, 727 $cm^{-1}$.

## Results and Discussion

**Monomer Synthesis.** Scheme 1 illustrates the synthetic procedure for the novel amino acid-based cyclic carbonate monomers, Z-S-CC, Z-T-CC, and Boc-T-CC. Z-Ser, Z-Thr, and Boc-Thr were transformed into mixed anhydrides by reaction with isobutyl chloroformate and reduced with $NaBH_4$.[11] The obtained diols were reacted with triphosgene in the presence of 2,3-dimethyl-1-phenyl-3-pyrazolin-5-one as a base to afford the cyclic carbonate monomers. The yield of each step was 70−80%.

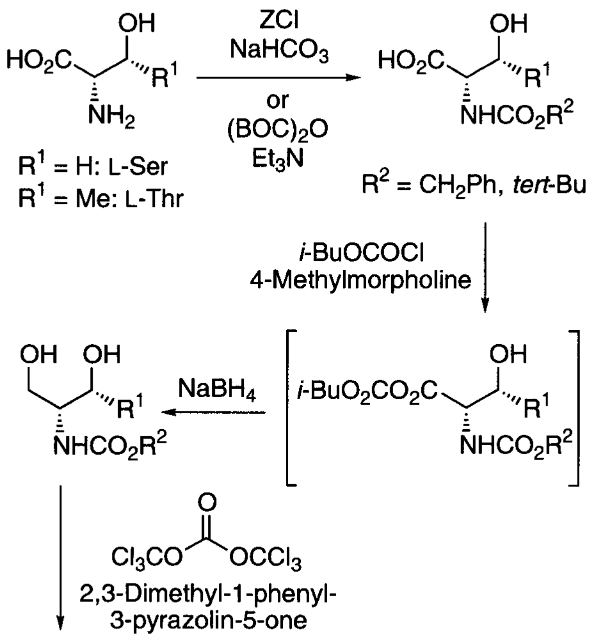
**Anionic Polymerization.** Scheme 2 and Table 1 summarize the anionic polymerization of Z-S-CC, Z-T-CC, and Boc-T-CC with *tert*-BuOK, *tert*-BuOLi, and *n*-BuLi as initiators in THF at −78 to −30 °C. The monomer conversion amounted to 32−93% to give white powdery polymers in 20−82% yields, which were isolated by precipitation with ether. At 0 and 40 °C, no polymer was obtained but ether-soluble low molecular weight compounds (40−50%), whose structures could not be determined. The polymerization at −78 °C

**Table 1. Anionic Ring-Opening Polymerization of Z-S-CC, Z-T-CC, and Boc-T-CC**[a]

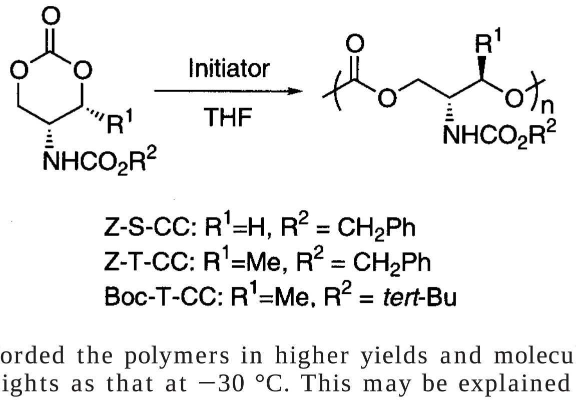
| run | monomer | $R^1$ | $R^2$ | initiator | mol % | temp (°C) | conv[b] (%) | yield[c] (%) | $M_n$[b] | $M_w/M_n$[b] | $[\alpha]_D$[d] (deg) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Z-S-CC | H | $PhCH_2$ | *tert*-BuOK | 2 | −78 | 70 | 62 | 14 000 | 1.30 | |
| 2 | Z-S-CC | H | $PhCH_2$ | *tert*-BuOK | 5 | −78 | 60 | 58 | 10 000 | 1.27 | |
| 3 | Z-S-CC | H | $PhCH_2$ | *tert*-BuOK | 10 | −78 | 84 | 68 | 6 900 | 1.46 | |
| 4 | Z-S-CC | H | $PhCH_2$ | *tert*-BuOK | 10 | −30 | 70 | 68 | 5 800 | 1.22 | |
| 5 | Z-S-CC | H | $PhCH_2$ | *tert*-BuOLi | 5 | −78 | 61 | 59 | 20 000 | 1.20 | |
| 6 | Z-S-CC | H | $PhCH_2$ | *tert*-BuOLi | 10 | −78 | 83 | 82 | 9 700 | 1.46 | |
| 7 | Z-S-CC | H | $PhCH_2$ | *tert*-BuOLi | 10 | −30 | 67 | 65 | 5 600 | 1.33 | |
| 8 | Z-S-CC | H | $PhCH_2$ | *n*-BuLi | 10 | −78 | 85 | 70 | 11 000[e] | 1.45 | |
| 9 | Z-T-CC | Me | $PhCH_2$ | *tert*-BuOK | 2 | −78 | 91 | 76 | 24 000 | 1.23 | +17.9 |
| 10 | Z-T-CC | Me | $PhCH_2$ | *tert*-BuOK | 5 | −78 | 93 | 78 | 16 000 | 1.24 | +18.3 |
| 11 | Z-T-CC | Me | $PhCH_2$ | *tert*-BuOLi | 2 | −78 | 37 | 22 | 13 000 | 1.17 | +13.8 |
| 12 | Z-T-CC | Me | $PhCH_2$ | *tert*-BuOLi | 5 | −78 | 32 | 20 | 13 000 | 1.18 | +14.9 |
| 13 | Boc-T-CC | Me | *tert*-Bu | *tert*-BuOK | 2 | −78 | [f] | 72 | 21 000 | 1.15 | +10.7 |
| 14 | Boc-T-CC | Me | *tert*-Bu | *tert*-BuOK | 5 | −78 | [f] | 67 | 14 000 | 1.20 | +12.3 |
| 15 | Boc-T-CC | Me | *tert*-Bu | *tert*-BuOLi | 2 | −78 | [f] | 51 | 11 000 | 1.11 | +13.8 |
| 16 | Boc-T-CC | Me | *tert*-Bu | *tert*-BuOLi | 5 | −78 | [f] | 49 | 5 700 | 1.11 | +13.5 |

[a] Conditions: monomer 1 mmol, solvent THF 5 mL, time 1 h. [b] Estimated by GPC based on polystyrene standards, eluent; LiBr solution in DMF (5.8 mM). The monomer conversion was estimated by GPC measurement of the crude polymerization mixture before isolation of the polymer. [c] Ether-insoluble part. [d] Measured by polarimetry at 25 °C ($c$ = 1.00, $CHCl_3$). [e] Bimodal peak. [f] Not determined.

**Scheme 1**



**Scheme 2**



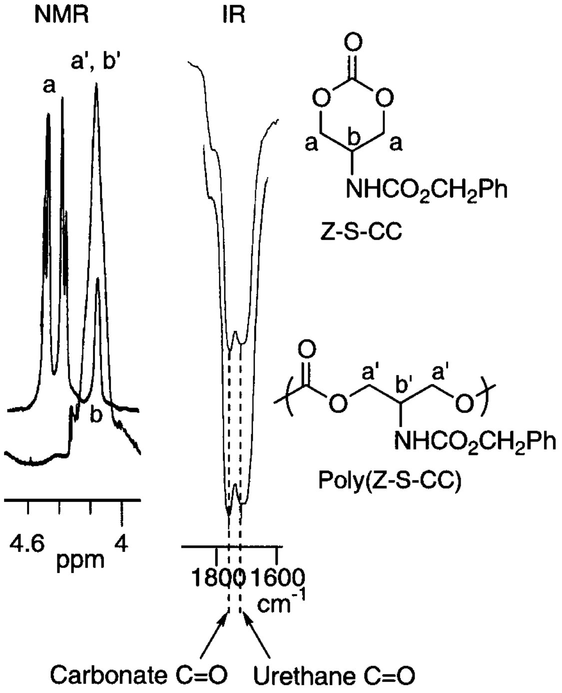
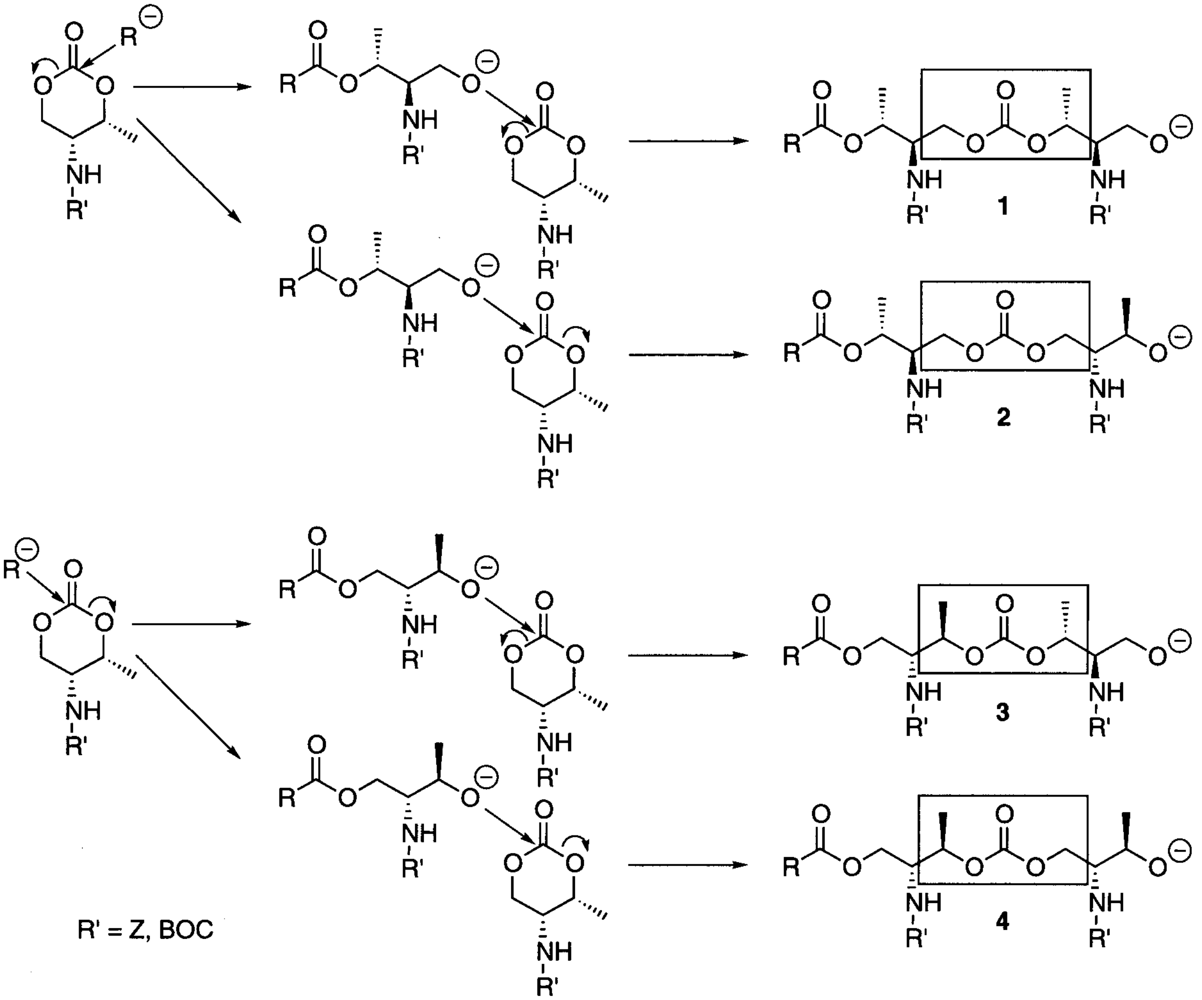


**Figure 1.** $^1H$ NMR and IR spectra of Z-S-CC [top] and poly(Z-S-CC) [bottom] obtained by polymerization with *tert*-BuOK (5 mol %) in THF at −78 °C for 1 h (run 2 in Table 1).

afforded the polymers in higher yields and molecular weights as that at −30 °C. This may be explained by the shift of equilibrium to the monomer side and suppression of side reactions such as proton abstraction of the urethane moiety at lower temperature. *tert*-BuOK and *tert*-BuOLi afforded polymers showing single modal GPC curves, but *n*-BuLi afforded a polymer showing a bimodal GPC curve (run 8). The highly nucleophilic alkyl anion would cause some side reactions forming different propagating species. The most plausible side reaction is the attack of butyl anion to the urethane moiety, forming benzyloxy anion. Runs 1−3 and 5−6 show the effect of the initiator concentration on the polymerization. The molecular weight increased with increasing the monomer/initiator ratio. In the polymerization of Z-T-CC and Boc-T-CC, *tert*-BuOLi resulted in lower monomer conversions and polymer yields compared with *tert*-BuOK under similar conditions, while no apparent difference was observed in monomer conversions and polymer yields in the polymerization of Z-S-CC. The polydispersity indices of the polymers from Z-T-CC and Boc-T-CC were smaller (1.11−1.24)

**Scheme 3**



than those from Z-S-CC (1.20−1.46). The polymers showed inverted specific rotations with respect to the monomers.

Figure 1 shows the partial $^1$H NMR and IR spectra of Z-S-CC and the polymer obtained with *tert*-BuOK (5 mol %) in THF at −78 °C for 1 h. The α-methylene proton signals of the carbonate moiety shifted ca. 0.3 ppm to higher field with broadening, typically observed in cyclic carbonate polymerization.[2] In the IR spectrum of the polymer, the carbonate and urethane carbonyl absorption peaks were observed in the same intensity ratios as the monomer at 1753 and 1718 cm$^{-1}$, respectively, supporting the polymer structure elucidated by $^1$H NMR spectroscopy.

**Ring-Opening Direction.** Z-T-CC and Boc-T-CC have the possibility of two ring-opening directions. Consequently, the formed polymers would have four diad sequences as illustrated in Scheme 3. The equimolar reaction of Boc-T-CC and *tert*-BuOK was carried out in THF at −78 °C for 30 min to obtain information on the selectivity of ring opening. Figure 2 shows the partial $^1$H and $^{13}$C NMR spectra of the product. The $^1$H NMR spectrum showed two methine and NH proton signals assignable to two isomers (**A** and **A′**), with the integration ratio of 89:11. The $^{13}$C NMR spectrum showed the corresponding methyl carbon signals with the integration ratio of 88:12. It was concluded that the product consisted of the two isomers with the ratio of ca. 9:1. The selectivity of the ring-opening directions may be explained on the basis of the steric hindrance due to the methyl group. Namely, an alkoxide anion should attack the carbonate carbonyl carbon preferably from the opposite direction of the methyl group to avoid steric hindrance (Scheme 4). The C−O bond closer to the methyl group cleaves, because of the pushing effect by the approaching anion. Therefore, it would be reasonable that adduct **A** was formed predominantly compared to adduct **A′**.

Figure 3 depicts the carbonate carbonyl signals of the $^{13}$C NMR spectrum of the polymer obtained by the polymerization of Boc-T-CC with *tert*-BuOK (2 mol %) in THF at −78 °C for 1 h. Three signals were observed in the integration ratio of 10:78:12.[12] We expected that the ratio would be changed by the addition of crown ether due to the steric effect of the countercationic part. Table 2 summarizes the results of polymerization of Z-T-CC and Boc-T-CC initiated with *tert*-BuOK in the absence and presence of dibenzo-18-crown-6. No apparent effect was observed by the addition of the crown ether on the diad sequence ratio, along with the polymer yield, molecular weight, polydispersity index, and specific rotation. The ratio of the three unit sequences is ca. 10:80:10, irrespective of the addition of the crown ether. From the equimolar reaction of Boc-T-CC with *tert*-BuOK as described above, it can be estimated that the ratio of the diad sequences of **1**, **2**, **3**, and **4** (Scheme 3) is 1:10:10:79. The diads **1** and **4** are indistinguishable. Consequently, the diad ratio is calculated to be 10:80:

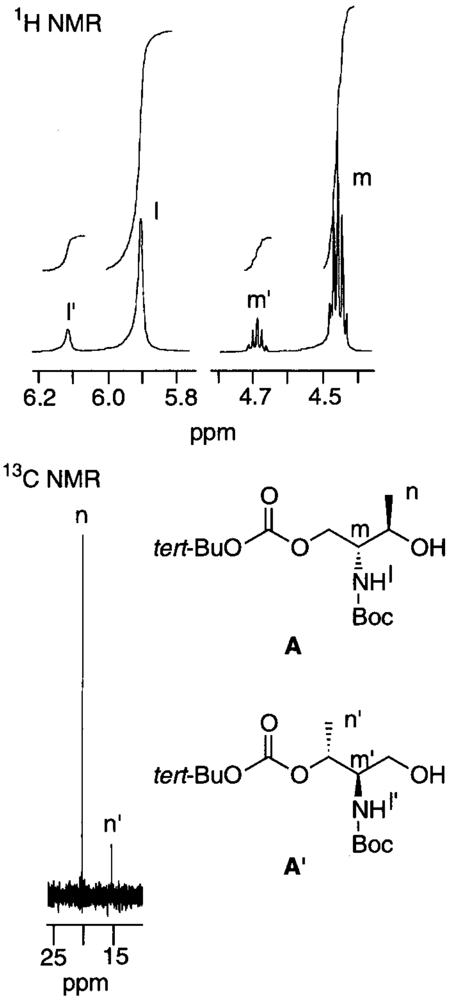


**Figure 2.** $^1$H and $^{13}$C NMR spectra of the adducts of Boc-T-CC with *tert*-BuOK.

10, which well agrees with the value of the polymer determined by $^{13}$C NMR spectroscopy.

**Cleavage of Z and Boc Groups.** The polycarbonates obtained by the polymerization of the Ser- and Thr-based cyclic carbonates have Z and Boc groups. Cleavage of the urethane-protecting groups should form novel polycarbonates with free amino groups. Poly(Z-S-CC) was submitted for hydrogenation catalyzed with palladium on carbon. Hydrogenation in ethyl acetate, acetic acid, and methanol resulted in no conversion but proceeded quantitatively in DMF. However, the polymer could not be separated from DMF and the catalyst. Employment of a mixed solvent of acetic acid/DMF (volume ratio 95:5) was satisfactory to achieve quantitative cleavage and product isolation. After hydrogenation, aromatic and benzyl proton signals at 7.2 and 5.0 ppm disappeared, and a broad signal assignable to amino protons appeared at 4.2−5.0 ppm. The $M_n$ of the polymer decreased from 18 000 ($M_w/M_n$ 1.25) to 4000 ($M_w/M_n$ 1.15) in accordance with the decrease of the molecular weight of the repeating unit. Fission of the polymer main chain during hydrogenation is negligible due to the single modal GPC and narrow polydispersity index of the polymer after hydrogenation. Increase of hydrophilicity may also be responsible for the molecular weight decrease determined by GPC. In fact, the formed polymer was highly deliquescent.

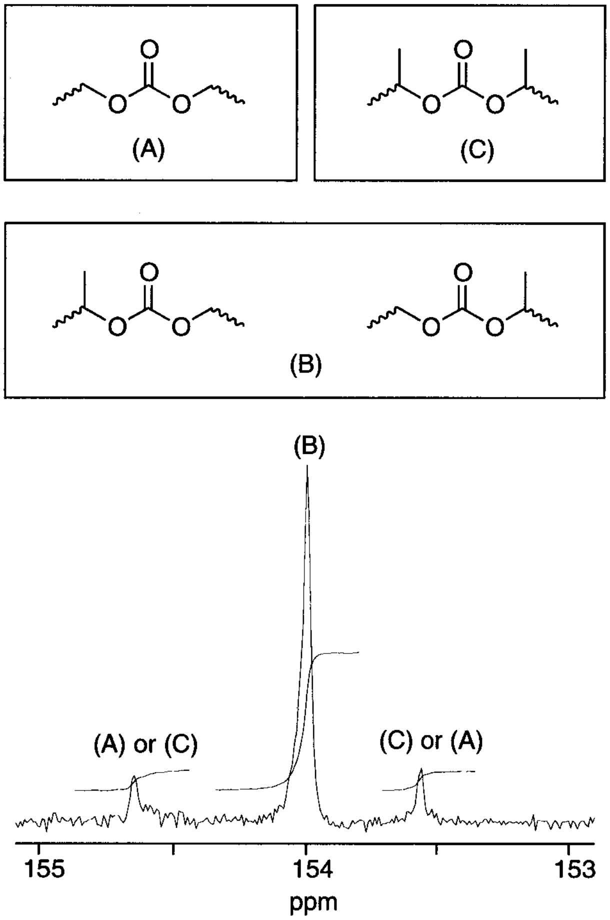
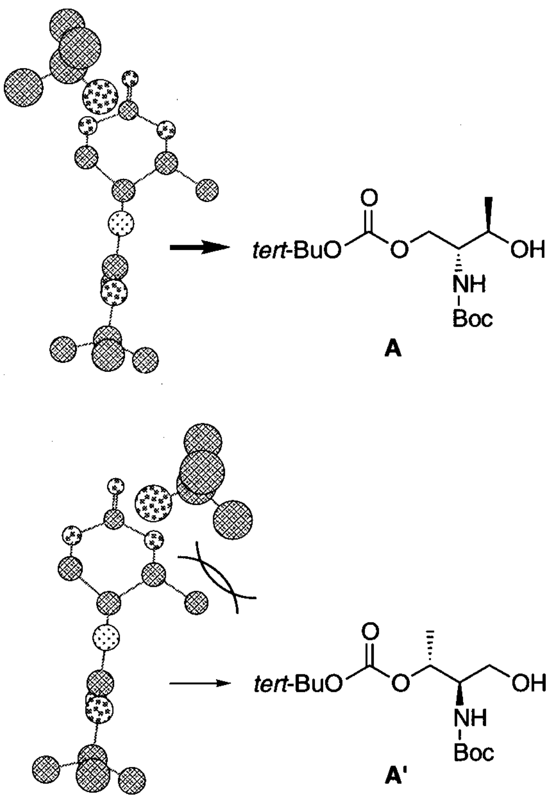


**Figure 3.** $^{13}$C NMR signals of carbonate carbonyl carbon of poly(Boc-T-CC) measured with pulse delay = 7 s.

**Scheme 4**



Acid cleavage of the Boc group was carried out using trifluoroacetic acid in dichloromethane at room temperature. Figure 4 shows the $^{13}$C NMR spectra before and after the reaction. Signals *f*, *g*, and *h* assignable to the

**Table 2. Anionic Ring-Opening Polymerization of Z-T-CC and Boc-T-CC in the Absence and Presence of Dibenzo-18-crown-6**[a]

| monomer | R$^1$ | R$^2$ | dibenzo-18-crown-6 (mol % vs monomer) | conv[b] (%) | yield[c] (%) | $M_n$ [b] | $M_w/M_n$[b] | sequence ratio[d] (%) | $[\alpha]_D$[e] (deg) |
|---|---|---|---|---|---|---|---|---|---|
| Z-T-CC | Me | $PhCH_2$ | 0 | 91 | 76 | 24 000 | 1.23 | 11:79:10 | +17.9 |
| Z-T-CC | Me | $PhCH_2$ | 2 | 90 | 67 | 22 000 | 1.23 | 6:84:10 | +19.5 |
| Boc-T-CC | Me | *tert*-Bu | 0 | f | 72 | 21 000 | 1.15 | 10:78:12 | +10.7 |
| Boc-T-CC | Me | *tert*-Bu | 2 | f | 83 | 22 000 | 1.17 | 10:77:13 | +12.5 |

[a] Conditions: monomer, 1 mmol, initiator *tert*-BuOK, 2 mol %, solvent THF 5 mL, temperature −78 °C, time 1 h. [b] Estimated by GPC based on polystyrene standards, eluent LiBr solution in DMF (5.8 mM). The monomer conversion was estimated by GPC measurement of the crude polymerization mixture before isolation of the polymer. [c] Ether-insoluble part. [d] Estimated by $^{13}$C NMR. [e] Measured by polarimetry at 25 °C ($c$ = 1.00, $CHCl_3$). [f] Not determined.

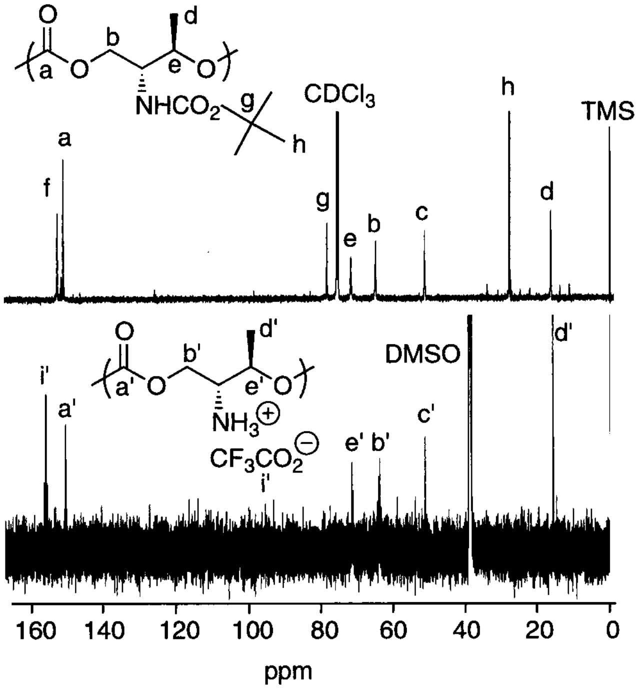


**Figure 4.** $^{13}$NMR spectra of poly(Boc-T-CC) [top] and the polymer obtained by the treatment with trifluoroacetic acid [bottom].

Boc group disappeared, and the carbonyl carbon signal *i'* of trifluoroacetate appeared after the reaction, indicating the proceeding of deprotection. In the IR spectra, the urethane carbonyl absorption peak at 1709 cm$^{-1}$ disappeared, and trifluoroacetate carbonyl peak appeared at 1678 cm$^{-1}$. The formed polymer was also deliquescent, but not as much as the polymer obtained by hydrogenation of poly(Z-S-CC), probably due to the presence of the hydrophobic methyl group.

**Supporting Information Available:** The procedures for the synthesis of Z-serinol, Z-threoninol, and Boc-threoninol. This material is available free of charge via the Internet at http://pubs.acs.org.

## References and Notes

(1) (a) Keul, H.; Bacher, R.; Höcker, H. *Makromol. Chem.* **1986**, *187*, 2579. (b) Kühling, S.; Keul, H.; Höcker, H. *Makromol. Chem.* **1990**, *191*, 161. (c) Bialas, N. J.; Kühling, S.; Keul, H.; Höcker, H. *Makromol. Chem.* **1990**, *191*, 1165. (d) Keul, H.; Deisel, F.; Höcker, H.; Leitz, E.; Ott, K. H.; Buysch, H. J.; Schön, N. *Makromol. Chem., Rapid Commun.* **1991**, *12*, 133. (e) Kühling, S.; Keul, H.; Höcker, H.; Buysch, H. J.; Schön, N.; Leitz, E. N. *Macromolecules* **1991**, *24*, 4229. (f) Albertsson, A.-C.; Sjöling, M. *J. Mol. Sci., Pure Appl. Chem.* **1992**, *A29*, 43. (g) Höcker, H.; Keul, H.; Kühling, S.; Hovestadt, W.; Müller, A.; Wurm, B. *Makromol. Chem., Macromol. Symp.* **1993**, *73*, 1. (h) Höcker, H.; Keul, H. *Macromol. Symp.* **1994**, *85*, 211. (i) Weilandt, K. D.; Keul, H.; Höcker, H. *Macromol. Chem. Phys.* **1996**, *197*, 2539. (j) Schmitz, F.; Keul, H.; Höcker, H. *Macromol. Rapid Commun.* **1997**, *18*, 699.

(2) Matsuo, J.; Aoki, K.; Sanda, F.; Endo, T. *Macromolecules* **1998**, *31*, 4432.

(3) (a) Kricheldorf, H. R.; Dunsing, R.; Albet, A. S. *Makromol. Chem.* **1987**, *188*, 2453. (b) Kricheldorf, H. R.; Jenssen, J. *J. Macromol. Sci.* **1989**, *A26*, 631.

(4) Kricheldorf, H. R.; Weegen-Schulz, B. *Polymer* **1995**, *36*, 4997.

(5) Kricheldorf, H. R.; Weegen-Schulz, B. *J. Polym. Sci., Part A: Polym. Chem.* **1995**, *33*, 2193.

(6) (a) Ariga, T.; Takata, T.; Endo, T. *J. Polym. Sci., Part A: Polym. Chem.* **1993**, *31*, 581. (b) Ariga, T.; Takata, T.; Endo, T. *Macromolecules* **1997**, *30*, 737.

(7) Takata, T.; Sanda, F.; Ariga, T.; Nemoto, H.; Endo, T. *Macromol. Rapid Commun.* **1997**, *18*, 461.

(8) Sugiyama, J.; Nagahata, R.; Goyal, M.; Asai, M.; Ueda, M.; Takeuchi, K. *ACS Polym. Prepr.* **1999**, *40* (1), 90.

(9) Matsumura, S.; Tsukada, K.; Toshima, K. *Macromolecules* **1997**, *30*, 3122.

(10) (a) Hey, D. H., John, D. I., Eds.; *Amino Acids, Peptides and Related Compounds*; Butterworths: London, 1973. (b) Sanda, F.; Endo, T. *Macromol. Chem. Phys.* **1999**, *200*, 2651.

(11) See Supporting Information.

(12) Pulse delay was set for 7 s to enhance the integration accuracy.

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