Regio- and Stereoselectivity in Cationic Cyclopolymerizations of 1,2:5,6-Dianhydro-3,4-di-*O*-methyl-D-mannitol and -L-iditol and the Synthesis of Poly[(1→6)-2,5-anhydro-3,4-di-*O*-methyl-D-glucitol]

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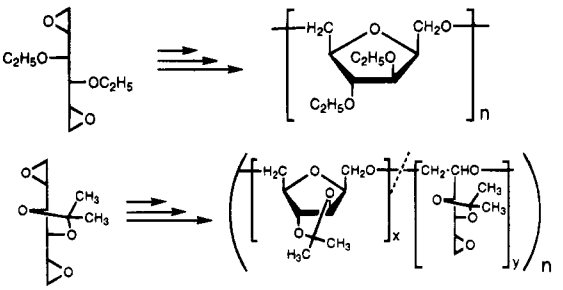
ABSTRACT: The cyclopolymerizations of 1,2:5,6-dianhydro-3,4-di-*O*-methyl-D-mannitol (**1**) and -L-iditol (**2**) were carried out using BF_3·OEt_2 and $SnCl_4$. The polymers obtained were soluble in chloroform, methanol, tetrahydrofuran, and water but insoluble in *n*-hexane. The specific rotations ($[\alpha]^{22}_{546}$) of the polymers were +41.3 to +73.2° for **1** and +38.2 to +62.9° for **2** (c = 1.0, $CHCl_3$). For all the polymers, the extent of cyclization was 100%. The structure of the polymers obtained from both **1** and **2** was (1→6)-bonded 2,5-anhydro-3,4-di-*O*-methyl-D-mannitol as the 5-membered constitutional unit, namely, poly-[(1→6)-2,5-anhydro-3,4-di-*O*-methyl-D-glucitol]. The *n*-hexane-soluble products, which were obtained together with the *n*-hexane-insoluble polymers for the polymerization using BF_3·OEt_2, contained 1,6:2,5-dianhydro-3,4-di-*O*-methyl-D-glucitol, the cyclic dimer of 2,5-anhydro-3,4-di-*O*-methyl-D-glucitol and its higher cyclic homologs.

Introduction

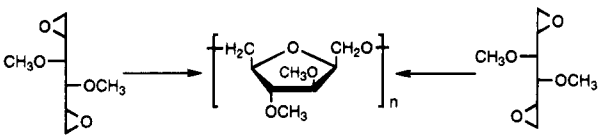
Recently, we reported that the cationic cyclopolymerization tendency of 1,2:5,6-dianhydro-D-mannitols was affected by the substituents at the 3,4-*O*-positions.[1] 3,4-*O*-Ethyl-substituted 1,2:5,6-dianhydro-D-mannitol was polymerized to form the polymer consisting of 2,5-anhydro-3,4-di-*O*-ethyl-D-glucitol as the cyclic constitutional repeating unit, i.e., poly[(1→6)-2,5-anhydro-3,4-di-*O*-ethyl-D-glucitol], whereas the monomer with the 3,4-di-*O*-isopropylidene group produced the polymers with cyclic and acyclic units (Scheme 1). For the polymerization of 1,2:5,6-dianhydro-3,4-di-*O*-ethyl-D-mannitol, we have proposed a regio- and stereoselective cyclopolymerization mechanism.[2] The intramolecular cyclization and the intermolecular reaction proceeded through α,β-scission of two epoxides in a monomer molecule to form the polymer consisting of (1→6)-bonded 2,5-anhydro-D-glucitol recurring units. According to the mechanism, the other diastereomer of 1,2:5,6-dianhydro-D-mannitol should also produce the same polymer structure. L-Iditol is a reliable candidate, because it possesses a C_2 symmetric axis as well as D-mannitol but differs from D-mannitol in absolute configuration at the C2 and C5 carbons, i.e., the *S,S* configuration for L-iditol and the *R,R* one for D-mannitol.

In this paper, we report the polymerizations of 1,2:5,6-dianhydro-3,4-di-*O*-methyl-D-manitol (**1**) and -L-iditol (**2**) using cationic initiators (Scheme 2). The polymer structures from **1** and **2** are confirmed by comparing the ^{13}C NMR spectra with that of 2,5-anhydro-1,3,4,6-tetra-*O*-methyl-D-glucitol (**4**). For both polymerizations of **1** and **2**, 1,6:2,5-dianhydro-3,4-di-*O*-methyl-D-glucitol (**5**) and the cyclic oligomers (**6**) are obtained as low molecular weight compounds. The regio- and stereoselective cyclopolymerization mechanism is discussed together with the cyclization tendency of **1** and **2**.

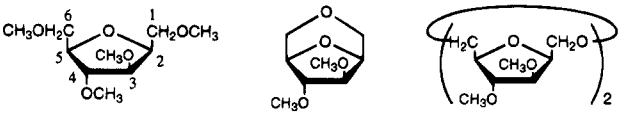
Scheme 1



Scheme 2



1 **2**



4 **5** **6**

Experimental Section

Measurement. ^1H and ^{13}C NMR spectra were recorded using a Bruker MSL 400 instrument. Optical rotation was

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determined with a Jasco DIP-140 digital polarimeter. IR spectra were taken with a Perkin-Elmer Paragon 1000 FT-IR spectrophotometer. FI and FD-MS were obtained with a JEOL JMS-SX102A mass spectrometer. The molecular weights of the resulting polymers were measured by gel permeation chromatography (GPC) in tetrahydrofuran on a Waters M45 high-performance liquid chromatograph equipped with three polystyrene gel columns (Shodex KF-804L). The number-average molecular weight (M_n) and the molecular weight distribution (M_w/M_n) were calculated on the basis of a polystyrene calibration.

Materials. Boron trifluoride etherate (BF_3·OEt_2) and tin(IV) chloride ($SnCl_4$) were purified by distillation of commercial products under reduced pressure. Dichloromethane, nitroethane, and toluene were purified by the usual methods and distilled over calcium hydride. Column chromatography was performed on silica gel 60 (particle size 0.063–0.200 mm, Merck). Thin-layer chromatography was performed on silica gel 60 F_{254} (0.25 mm thick, Merck).

Monomer Preparation. 1,2:5,6-Dianhydro-3,4-di-*O*-methyl-D-mannitol (1). Monomer **1** was prepared from D-mannitol according to the method of Kuszmann.[3] Mp = 11–12 °C (lit. mp = 17–19 °C); $bp_{0.3}$ = 68–70 °C (lit. $bp_{1.5}$ = 95–97 °C); $[\alpha]_D$ −9.4°, $[\alpha]_{546}$ −12.3° (*c* = 1.0 in $CHCl_3$ at 22 °C) (lit. $[\alpha]_D$ −10°, in $CHCl_3$ at 20 °C); ^1H NMR ($CDCl_3$) δ = 3.49 (s, OCH_3, 6H), 3.13–3.16 (m, epoxy CH and CHO, 4H), 2.86–2.93 (m, *cis*-CH_2, 2H), 2.77–2.82 ppm (m, *trans*-CH_2, 2H); ^{13}C NMR ($CDCl_3$) δ 81.04 (*C*HOCH$_3$), 59.29 (OCH_3), 50.02 (CH), 46.51 ppm (CH_2).

1,2:5,6-Dianhydro-3,4-di-*O*-methyl-L-iditol (2). Monomer **2** was prepared from D-mannitol.[3] Mp = 38–40 °C (lit. mp = 40–42 °C); $bp_{0.3}$ = 65–66 °C (lit. $bp_{0.1}$ = 70–72 °C); $[\alpha]_{546}$ −9.8° (*c* = 1.0 in $CHCl_3$ at 22 °C); ^1H NMR ($CDCl_3$) δ = 3.51 (s, OCH_3, 6H), 3.14–3.21 (m, epoxy CH, 2H), 3.00–3.05 (m, CHO, 2H), 2.81 (dd, J_{gem} = 5.0 Hz, $^3J_{cis}$ = 4.3 Hz, *cis*-CH_2, 2H), 2.60 ppm (dd, J_{gem} = 5.0 Hz, $^3J_{trans}$ = 2.6 Hz, *trans*-CH_2, 2H); ^{13}C NMR ($CDCl_3$) δ 82.95 (*C*HOCH$_3$), 58.64 (OCH_3), 52.03 (CH), 42.83 ppm (CH_2).

2,5-Anhydro-3,4-di-*O*-methyl-D-glucitol (3). A mixture of **2** (1.74 g, 10 mmol) and 40 mL of water was heated under reflux for 7 h and then the solution was evaporated under reduced pressure to obtain a syrup from which the water was removed by two azeotropic distillations with benzene and chloroform. The syrup was purified by flash column chromatography using ethyl acetate/2-propanol (5/1). The fractions having an R_f 0.5 gave, on evaporation, pure **3** as a colorless syrup (1.44 g, 75%). $[\alpha]_{546}$ +87.3°(c 1.0 in $CHCl_3$ at 22 °C); IR (film) 3370 (OH), 2920, 2870, 2810 (ν, C–H), 1085 cm^{-1} (ν_{as}, C–O–C); ^1H NMR ($CDCl_3$) δ = 4.08 (dt, J = 4.9 Hz, J = 4.4 Hz, H2, 1H), 3.91 (td, J = 4.4 Hz, J = 3.2 Hz, H5, 1H), 3.80–3.88 (m, H3, H1, H6A, 4H), 3.81 (dd, J = 4.3 Hz, J = 2.1 Hz, H4, 1H), 3.69 (dd, J = 11.9 Hz, J = 4.3 Hz, H6B, 1H), 3.43 (s, CH_3O, 6H), 3.15 ppm (br s, HO, 2H); ^{13}C NMR ($CDCl_3$) δ = 86.19 (C3), 84.37 (C4), 83.52 (C5), 80.26 (C2), 62.78 (C6), 61.42 (C1), 57.63 (CH_3O), 57.495 ppm (CH_3O). The hydrolysis of **1** also gave an 82% yield of **3**; $[\alpha]_{546}$ +88.1°(*c* = 1.0 in $CHCl_3$ at 22 °C); ^{13}C NMR ($CDCl_3$) δ = 86.17, 84.44, 83.60, 80.38, 62.85, 61.47, 57.71, 57.55 ppm.

2,5-Anhydro-1,3,4,6-tetra-*O*-methyl-D-glucitol (4). To a stirred solution of **3** (1.44 g, 7.5 mmol) in 9.6 mL of dimethyl sulfoxide was simultaneously added a solution of sodium hydroxide (1.5 g, 37.5 mmol) in 1.5 mL of water and dimethyl sulfate (2.40 g, 19 mmol) at such a rate that the temperature of the reaction mixture did not exceed 60 °C. Stirring was continued at this temperature for 30 min. After standing overnight at room temperature, the mixture was poured into water and extracted with chloroform. The extract was dried, and the residue was purified by column chromatography with *n*-hexane/diethyl ether (1/1). Evaporation of the fractions having an R_f 0.45 gave pure **4** as a colorless syrup (0.78 g, 47.3%); $[\alpha]_D$ +66.7°, $[\alpha]_{577}$ +69.8°, $[\alpha]_{546}$ +78.6°, $[\alpha]_{435}$ +130.1°, $[\alpha]_{405}$ +155.4° (*c* = 1.06 in $CHCl_3$ at 20 °C); IR (film) 2975, 2900, 2890, 2810 (ν, C–H), 1100 cm^{-1} (ν_{as}, C–O–C); ^1H NMR ($CDCl_3$) δ = 4.09 ($^3J_{H6A,H5}$ = 6.8 Hz, $^3J_{H6B,H5}$ = 5.0 Hz, $^3J_{H5,H4}$ = 4.3 Hz, H5, 1H), 3.92 ($^3J_{H2,H1A}$ = 5.9 Hz, $^3J_{H2,H1B}$ = 5.9 Hz, $^3J_{H2,H3}$ = 3.6 Hz, H2, 1H), 3.68 ($^3J_{H4,H5}$ = 4.1 Hz, $^3J_{H4,H3}$ = 0.8 Hz, H4, 1H), 3.64 ($^3J_{H3,H2}$ = 3.9 Hz, $^3J_{H3,H4}$ = 1.2 Hz, H3), 3.64 (A) and 3.59 (B) ($^3J_{H6A,H5}$ = 6.8 Hz, $^3J_{H6B,H5}$ = 5.0 Hz, $^2J_{H6A,H6B}$ = 10.2 Hz, H6, 2H), 3.55 (A) and 3.47 (B) ($^3J_{H1A,H2}$ = 6.0 Hz, $^3J_{H1B,H2}$ = 5.9 Hz, $^2J_{H1A,H1B}$ = 10.0 Hz, H1, 2H), 3.40 (CH_3O on C1), 3.40 (CH_3O on C6), 3.39 (CH_3O on C4), 3.38 ppm (CH_3O on C3); ^{13}C NMR ($CDCl_3$): δ = 85.69 (C3), 84.75 (C4), 82.26 (C2), 79.83 (C5), 73.15 (C1), 70.66 (C6), 59.25 and 59.19 (CH_3O on C6 and C1), 57.42 and 57.35 ppm (CH_3O on C3 and C4). Anal. Calcd for $C_{10}H_{20}O_5$: C, 54.53; H, 9.15. Found: C, 53.97; H, 9.25.

1,6:2,5-Dianhydro-3,4-di-*O*-methyl-D-glucitol (5). Compound **5** was prepared from **1** according to the known method.[4] R_f = 0.35 (*n*-hexane/ethyl acetate = 1/1); $[\alpha]_D$ −19.2°, $[\alpha]_{577}$ −20.2°, $[\alpha]_{546}$ −22.8°, $[\alpha]_{435}$ −39.3°, $[\alpha]_{435}$ −47.6° (*c* = 1.0, in $CHCl_3$ at 22 °C) (lit. $[\alpha]_D$ −22.5°, in $CHCl_3$ at 20 °C); ^1H NMR ($CDCl_3$) δ = 4.24 (br d, J = 6.1 Hz, H2, 1H), 4.01 (s, H5, 1H), 4.00 (s, H4, 1H), 3.93 (ddd, J = 6.3 Hz, J = 1.3 Hz, J = 1.0 Hz, H3, 1H), 3.84 (dd, J = 11.5 Hz, J = 1.7 Hz, H6, 1H), 3.79 (d, J = 1.5 Hz, H1, 2H), 3.66 (dt, J = 11.6 Hz, J = 1.0 Hz, H6, 1H), 3.49 (s, CH_3O, 3H), 3.41 ppm (s, CH_3O, 3H); ^{13}C NMR ($CDCl_3$) δ = 87.70 (C4), 87.64 (C3), 79.05 (C5), 76.37 (C2), 69.20 (C1), 65.43 (C6), 58.58 (OCH_3), 56.88 ppm (OCH_3); IR (film) 2940, 2900, 2850, 2825, 1216, 1110, 1104, 1070, 885 cm^{-1}.

Typical Polymerization Procedure. Monomer **1** (500 mg, 2.87 mmol) was dissolved in dry CH_2Cl_2 (5.74 mL), and then BF_3·OEt_2 (3.62 μL, 0.0287 mmol) was added using a microsyringe. After 24 h at 0 °C, the solution was poured into a large amount of methanol containing a drop of aqueous ammonia, and the solvent was then evaporated under reduced pressure. The residue was washed using *n*-hexane and dried under vacuum to give 245 mg (yield, 48.9%) of the polymer; the M_n and M_w/M_n were 2650 and 2.03, respectively. $[\alpha]_D$ +32.8 °, $[\alpha]_{577}$ +36.2°, $[\alpha]_{546}$ +41.3°, $[\alpha]_{435}$ +69.3°, $[\alpha]_{405}$ +82.5° (*c* = 1.0 in $CHCl_3$ at 22 °C); ^{13}C NMR ($CDCl_3$) δ = 85.41 (CH), 84.68 (CH), 82.27 (CH), 79.86 (CH), 71.72 (CH_2), 69.32 (CH_2), 57.32 ppm (OCH_3).

The polymerization of monomer **2** (500 mg, 2.87 mmol) was carried out by following the above procedure to obtain 227 mg (yield, 45.4%) of the polymer with an M_n of 1430 and M_w/M_n of 1.97. $[\alpha]_D$ +35.2 °, $[\alpha]_{577}$ +36.7°, $[\alpha]_{546}$ +43.1°, $[\alpha]_{435}$ +70.4°, $[\alpha]_{405}$ +82.6° (*c* = 1.0 in $CHCl_3$ at 22 °C); ^{13}C NMR ($CDCl_3$) δ = 85.45 (CH), 84.68 (CH), 82.27 (CH), 79.86 (CH), 71.74 (CH_2), 69.34 (CH_2), 57.34 ppm (OCH_3).

Oligomer Separation. After the *n*-hexane-insoluble polymer was separated, the filtrate was evaporated, and the residue was purified by thin-layer chromatography with ethyl acetate/*n*-hexane (1/1). Evaporation of the fractions having R_f 0.48 gave 150 mg (yield, 30%) of the compound whose ^1H and ^{13}C NMR spectra and physical properties were identical with those of **5**. FI-MS: *m/z* (relative intensity) 174 (M^+, 100), 175 ($(M + 1)^+$, 10.7), 176 (2.0).

Evaporation of the fractions having R_f 0.25 gave 30 mg (yield, 6%) of compound **6**. $[\alpha]_{577}$ −2.4°, $[\alpha]_{546}$ −4.2°, $[\alpha]_{435}$ −6.4°, $[\alpha]_{435}$ −7.2° (*c* = 1.0 in $CHCl_3$ at 23 °C); ^1H NMR ($CDCl_3$) δ = 4.53 (dd, J = 8.2 Hz, J = 7.9 Hz, H4, 1H), 4.20 (dd, J = 7.9 Hz, J = 2.6 Hz, H2, 1H), 4.03 (dd, J = 8.2 Hz, J = 7.9 Hz, H3, 1H), 3.79 (s, H6, 1H), 3.76 (dd, J = 6.3 Hz, J = 2.3 Hz, H5, 1H), 3.54–3.67 (m, H1 and H6, 2H), 3.52 (s, CH_3O, 3H), 3.47 (s, CH_3O, 3H), 3.35–3.46 ppm (m, H1, 1H); ^{13}C NMR ($CDCl_3$) δ = 85.59 (C3), 82.19 (C4), 79.91 (C5), 76.50 (C2), 70.82 (C6), 69.74 (C1), 58.78 (OCH_3), 56.62 ppm (OCH_3); FI-MS *m/z* (relative intensity) 348 (M^+, 100), 349 ($(M + 1)^+$, 55.2), 350 (17.5).

The *n*-hexane-soluble products for **2** were isolated by following the above procedure. Evaporation of the fractions having R_f 0.48 (ethyl acetate/*n*-hexane = 1/1) gave 90 mg (yield, 18%) of compound **5**. Evaporation of the fractions having R_f 0.25 gave 50 mg (yield, 10%) of compound **6**.

Model Cyclization. A solution of **1** (0.5 g, 2.87 mmol) in methanol containing a drop of hydrochloric acid was stirred at room temperature for 24 h. The mixture was neutralized by adding methanolic sodium methoxide and then evaporated under reduced pressure. The residue was purified by column chromatography to yield 2,5-anhydro-3,4,6-tri-*O*-methyl-D-glucitol (**7**) (0.41 g, 70%) and 2,6-anhydro-3,4,5-tri-*O*-methyl-L-iditol (**8**) (0.16 g, 28%). **7**: $[\alpha]_D$ +54.7°, $[\alpha]_{577}$ +57.0°, $[\alpha]_{546}$

Table 1. Cationic Polymerization of 1,2:5,6-Dianhydro-3,4-di-*O*-methyl-D-mannitol (1)[a]

Cat.	solvent	temp, °C	yield, %	M_n[b]	M_w/M_n[b]	[α],[c] deg
BF_3·OEt_2	$C_6H_5CH_3$	−30	12.5	1010	1.77	+64.5
	CH_2ClCH_2Cl	−30	42.7	1490	2.68	+62.6
	CH_2Cl_2	−30	68.3	1300	2.51	+70.4
	$C_2H_5NO_2$	−30	28.1	1080	1.94	+71.3
	$C_6H_5CH_3$	0	51.9[d]	3370	2.38	+63.5
	CH_2Cl_2	0	48.9	2650	2.03	+41.3
	$C_6H_5NO_2$	0	40.5	1450	2.33	+73.2
	$C_2H_5NO_2$	0	51.4	1730	1.73	+52.9
$SnCl_4$	CH_2Cl_2	−30	trace	1700	1.66	+59.2
	CH_2Cl_2	0	7.9	2500	2.26	+46.2

[a] [1] = 0.5; [1]/[Cat.] = 100; time = 24 h. [b] Measured in THF by GPC using PSt as standard. [c] Measured in $CHCl_3$ (*c* 1.0). [d] Organic solvent-insoluble polymer was 14.6%.

Table 2. Cationic Polymerization of 1,2:5,6-Dianhydro-3,4-di-*O*-methyl-L-iditol (2)[a]

Cat.	solvent	temp, °C	yield, %	M_n[b]	M_w/M_n[b]	[α],[c] deg
BF_3·OEt_2	$C_6H_5CH_3$	−30	trace	790	1.58	+45.1
	CH_2ClCH_2Cl	−30	5.5	570	1.53	+45.1
	CH_2Cl_2	−30	6.1	790	2.03	+45.1
	$C_2H_5NO_2$	−30	6.5	630	1.33	+44.8
	$C_6H_5CH_3$	0	15.5[d]	1450	1.54	+62.9
	CH_2Cl_2	0	45.4	1430	1.97	+43.1
	$C_6H_5NO_2$	0	35.7	1560	1.57	+52.3
	$C_2H_5NO_2$	0	20.7	950	1.28	+42.5
$SnCl_4$	CH_2Cl_2	−30	trace	1430	1.29	+42.3
	CH_2Cl_2	0	6.7	1720	1.81	+38.2

[a] [2] = 0.5; [2]/[Cat.] = 100; time = 24 h. [b] Measured in THF by GPC using PSt as standard. [c] Measured in $CHCl_3$ (*c* 1.0). [d] Organic solvent-insoluble polymer was 12.4%.

+64.1°, $[\alpha]_{435}$ +105.3°, $[\alpha]_{405}$ +123.3° (*c* = 1.0 in $CHCl_3$ at 23°C); ^{1}H NMR ($CDCl_3$) δ = 4.08 (dt, *J* = 4.9 Hz, *J* = 4.8 Hz, H2, 1H), 3.92 (td, *J* = 5.0 Hz, *J* = 4.9 Hz, H5, 1H), 3.84 (dd, *J* = 5.1 Hz, *J* = 2.7 Hz, H3, 1H), 3.82 (br d, *J* = 4.2 Hz, H1, 2H), 3.74 (dd, *J* = 4.7 Hz, *J* = 2.8 Hz, H4, 1H), 3.55 (d, *J* = 5.4 Hz, H6, 2H), 3.43 (s, OCH_3 on C3 and C4, 6H), 3.42 (s, OCH_3 on C6, 3H), 2.70 ppm (br s, OH, 1H); ^{13}C NMR ($CDCl_3$) δ = 86.04 (C3), 84.97 (C4), 81.32 (C5), 80.06 (C2), 73.20 (C6), 61.47 (C1), 59.25 (OCH_3 on C6), 57.71 and 57.65 ppm (OCH_3 on C3 and C4). Anal. Calcd for $C_9H_{18}O_5$: C, 52.41; H, 8.80. Found: C, 51.63; H, 8.75. FI-MS *m/z* (relative intensity) 206 (M^+ − 40.6), 207 (MH^+ − 100), 208 (15.9), 413 ($(2M + H)^+$ − 40.2), 414 (12.1). **8**: $[\alpha]_D$ +39.3°, $[\alpha]_{577}$ +42.5°, $[\alpha]_{546}$ +48.0°, $[\alpha]_{435}$ +80.4°, $[\alpha]_{405}$ +93.4° (*c* = 1.0 in $CHCl_3$ at 23 °C); ^{1}H NMR ($CDCl_3$) δ = 3.89−3.96 (m, H1 and H6, 2H), 3.75−3.80 (m, H5, 1H), 3.72 (dd, *J* = 12.4 Hz, *J* = 2.7 Hz, H1, 1H), 3.67 (dd, *J* = 11.5 Hz, *J* = 4.1 Hz, H6, 1H), 3.56 (t, *J* = 3.9 Hz, H3, 1H), 3.48 (s, OCH_3, 3H), 3.45 (s, OCH_3, 3H), 3.44 (s, OCH_3, 3H), 3.25−3.28 (m, H4, 1H), 3.19−3.23 (m, H2, 1H), 2.41 ppm (br s, OH, 1H); ^{13}C NMR ($CDCl_3$) δ = 76.85 (C4), 76.09 (C2), 75.53 (C5), 74.59 (C3), 64.43 (C6), 61.78 (C1), 58.39 (OCH_3), 57.71 (OCH_3), 57.62 ppm (OCH_3). Anal. Calcd for $C_9H_{18}O_5$: C, 52.41; H, 8.80. Found: C, 51.97; H, 8.78. FI-MS *m/z* (relative intensity) 206 (M^+ − 100), 207 (MH^+ − 37.8), 208 (5.6), 413 ($(2M + H)^+$ − 7.1).

From **2** (0.5 g, 2.87 mmol) for 48 h, 2,5-anhydro-1,3,4-tri-*O*-methyl-D-glucitol (**9**) (0.36 g, 60%) was isolated, a mixture (0.07 g, 12%) of compounds with *m/z* = 192 and 206 was separated, and 21% of **2** was recovered. **9**: $[\alpha]_D$ +80.5°, $[\alpha]_{577}$ +85.4°, $[\alpha]_{546}$ +94.4°, $[\alpha]_{435}$ +156.7°, $[\alpha]_{405}$ +187.7° (*c* = 1.0 in $CHCl_3$ at 23 °C); ^{1}H NMR ($CDCl_3$) δ = 4.13 (dt, *J* = 6.6 Hz, *J* = 4.3 Hz, H2, 1H), 3.93 (td, *J* = 3.4 Hz, *J* = 3.1 Hz, H5, 1H), 3.85 (br d, *J* = 11.7 Hz, H6, 1H), 3.80 (dd, *J* = 3.5 Hz, *J* = 1.3 Hz, H4, 1H), 3.70 (dd, *J* = 3.9 Hz, *J* = 1.2 Hz, H4, 1H), 3.69−3.56 (m, H6 and H1, 3H), 3.41 (s, OCH_3, 6H), 3.39 (s, OCH_3, 3H), 2.37 ppm (br s, OH, 1H); ^{13}C NMR ($CDCl_3$) δ = 84.47 (C3), 84.29 (C4), 84.22 (C5), 79.70 (C2), 70.66 (C1), 62.85 (C6), 59.20 (OCH_3 on C1), 57.71 and 57.65 ppm (OCH_3 on C4 and C3). Anal. Calcd for $C_9H_{18}O_5$: C, 52.41; H, 8.80. Found: C, 51.61; H, 8.74. FI-MS *m/z* (relative intensity) 206 (M^+ − 89.6), 207 (MH^+ − 100), 208 (13.8), 413 ($(2M + H)^+$ − 44.1), 414 (11.6).

Results

Polymerizations of 1,2:5,6-Dianhydro-3,4-di-*O*-methyl-D-mannitol and -L-iditol. Table 1 lists the results of the polymerization of 1,2:5,6-dianhydro-3,4-di-*O*-methyl-D-mannitol (**1**). For the polymerizations using BF_3·OEt_2, the reaction systems were homogeneous except for that in toluene as a solvent. The products obtained were sticky, semisolid, and soluble in chloroform, methanol, tetrahydrofuran, and water but insoluble in *n*-hexane. For the polymerization in dichloromethane at −30 °C, the highest polymer yield obtained was 68.3%. The polymerization in toluene at 0 °C proceeded heterogeneously, and the organic solvent-soluble polymer was obtained in 51.9% yield together with the organic solvent-insoluble one in 14.6% yield. After 24 h of polymerization time, **1** was recovered in slight amounts for the polymerizations at −30 °C though completely consumed for those at 0 °C. The *n*-hexane-soluble, low molecular weight products were obtained after separating the *n*-hexane-insoluble polymer. The number-average molecular weights (M_n) of the *n*-hexane-insoluble polymers obtained at −30 °C were 1010−1490, which corresponded to average degrees of polymerization (DP) of 5.8−8.6, while those at 0 °C were 1450−3370 (DP = 8.3−19.4).

Table 2 lists the results of the polymerization of 1,2:5,6-dianhydro-3,4-di-*O*-methyl-L-iditol (**2**). The polymerization using BF_3·OEt_2 proceeded homogeneously except for that in toluene. The *n*-hexane-insoluble polymers were sticky and semisolid, and their solubilities were similar to those from **1**. After the polymerization was terminated, small amounts of **2** were recovered and the *n*-hexane-soluble, low molecular weight products were also obtained. For all the polymerization conditions, the yields and M_ns for the polymers from **2** were lower than those from **1**. The M_ns of the polymers obtained at −30 °C were 570−790, which correspond to DP = 3.8−4.5, and those at 0 °C were 950−1560 (DP = 5.5−9.0).

For the polymerizations of **1** and **2** using $SnCl_4$ for 24 h, the polymer yields were very low, most of the monomers were recovered, and the *n*-hexane-soluble oligomers were not produced. The obtained polymers were sticky and semisolid, and the M_ns were 1700 and 2500 for **1** and 1430 and 1720 for **2**.

The specific rotations ($[\alpha]_{546}$) of the polymers were +41.3 to +73.2° for **1** and +38.2 to +62.9° for **2** (*c* = 1.0 in $CHCl_3$ at 22 °C). However, for both polymers, the obvious relation between the specific rotation and the M_n was not observed.

Polymer Structure. Figure 1 shows the ^{1}H NMR spectra of the polymers obtained from **1** and **2**. Since the characteristic signals at 3.13−3.16 and 2.77−2.93 ppm for **1** and at 3.14−3.21 and 2.60−2.81 ppm for **2** due to the epoxy groups completely disappeared, both polymerizations proceeded according to a cyclopolymerization mechanism leading to the polymers with cyclic constitutional repeating units, i.e., the extent of cyclization was 100%.

For the cationic polymerization of monosubstituted epoxides through an S_N2-type mechanism, the configuration of the asymmetric carbon atom is inversion due to ring opening at the CH−O bond (α-scission) and retention by the CH_2−O bond (β-scission).[5] Scheme 3

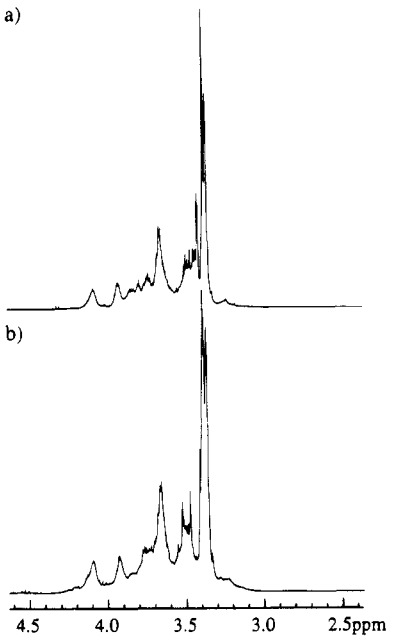
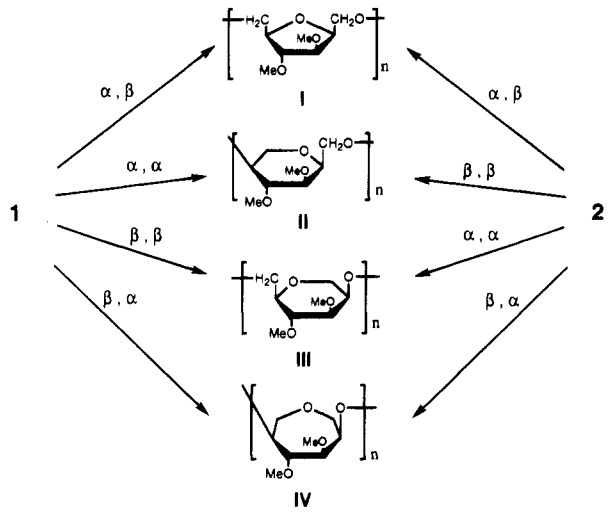


Figure 1. ^{1}H NMR spectra of polymers prepared from 1,2:5,6-dianhydro-3,4-di-*O*-methyl-D-mannitol (**1**) (a) and -L-iditol (**2**) (b), respectively.

Scheme 3[a]



[a] The former and latter symbols correspond to the intramolecular and intermolecular scissions, respectively.

represents the possible cyclic units formed through the S_N2-type mechanism. For the polymerization of **1**, the intramolecular cyclization and the intermolecular reaction through α,α- and β,β-scissions of the two epoxides in a monomer molecule formed the 6-membered rings **II** and **III**, respectively, whereas α,β- and β,α-scissions lead to the formation of the 5- and 7-membered rings **I** and **IV**, respectively. On the other hand, for the polymerization of **2**, the α,α- and β,β-scissions lead to the 6-membered rings **III** and **II**, respectively, which is opposite to **1**, while α,β- and β,α-scissions lead to the formation of 5- and 7-membered rings **I** and **IV**, respectively, as well as **1**.

To confirm the cyclic units in the polymers from **1** and **2**, 2,5-anhydro-1,3,4,6-tetra-*O*-methyl-D-glucitol (**4**) was synthesized from both **1** and **2** using the procedure of Wiggins et al.,[6] as shown in Scheme 4. Figure 2 shows the ^{13}C NMR spectra of **4** and the polymers from **1** and **2**. Each signal was assigned as follows: for the polymer from **1**, the signals at 85.41, 84.68, 82.27, and 79.86 ppm

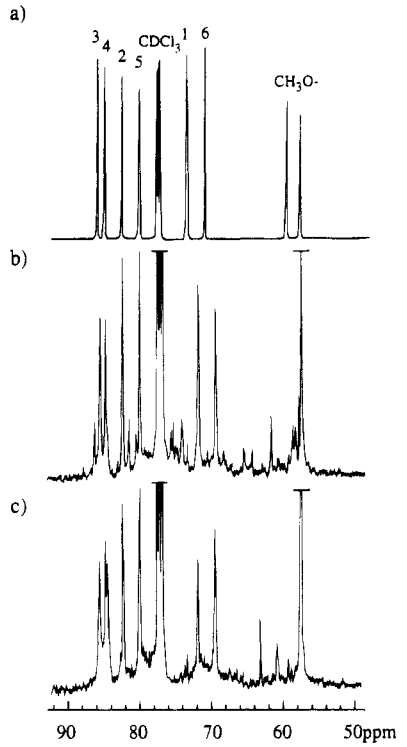
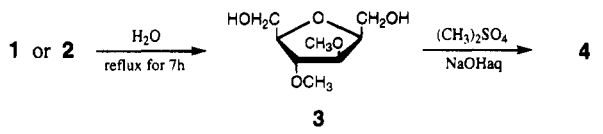


Figure 2. ^{13}C NMR spectra of 2,5-anhydro-1,3,4,6-tetra-*O*-methyl-D-glucitol (**4**) (a) and polymers prepared from 1,2:5,6-dianhydro-3,4-di-*O*-methyl-D-mannitol (**1**) (b) and -L-iditol (**2**) (c), respectively.

Scheme 4

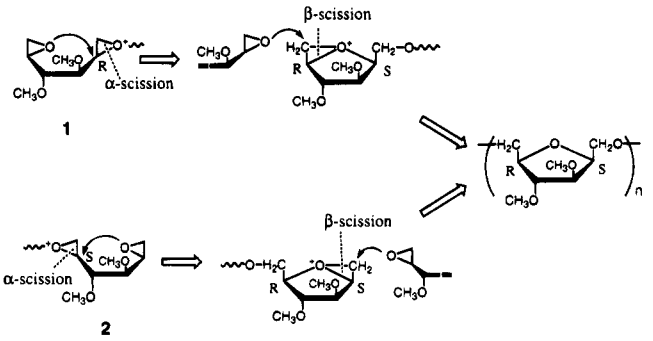


were the methine carbons and those at 71.72 and 69.32 ppm, the methylene ones, and for the polymer from **2**, the signals at 85.45, 84.68, 82.27, and 79.86 ppm were the methine carbons and those at 71.75 and 69.34 ppm, the methylene ones. Both of the four-signal spectra due to the methine carbons are very close to those at 82.30, 84.32, 83.16, and 79.74 ppm assigned to the carbons of C2, C3, C4, and C5 carbons, respectively, for **4**. This result indicates that the structure of the polymers from both **1** and **2** is (1→6)-bonded 2,5-anhydro-3,4-di-*O*-methyl-D-mannitol as the 5-membered constitutional unit of polymer (i.e., **I** in Scheme 3).

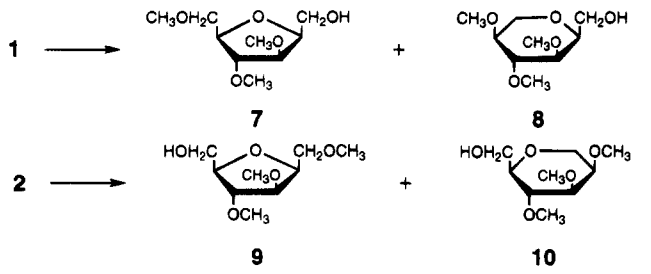
Oligomer Structure. Most of the monomers were retained for the polymerization using $SnCl_4$. On the other hand, after almost all of the monomers were consumed, the appropriate amount of the *n*-hexane-soluble products were obtained together with the *n*-hexane-insoluble polymers for the polymerization using BF_3·OEt_2. After purification by preparative thin-layer chromatography, an identical compound with $m/z = 174$ and $[\alpha]^{22}_{546} = -22.8°$ (c = 1.0, $CDCl_3$) was isolated in 30 and 18% yields for the polymerizations of **1** and **2** with BF_3·OEt_2, respectively. The structure of the isolated product was confirmed to be 1,6:2,5-dianhydro-3,4-di-*O*-methyl-D-glucitol (**5**) by comparison of its ^{1}H and ^{13}C NMR spectra and its chiroptical property.

In addition, the compound with m/z = 348 was obtained in 6 and 10% yield for **1** and **2**, respectively, which was estimated to be the cyclic dimer of 2,5-anhydro-3,4-di-*O*-methyl-D-glucitol (**6**). In the mass spectrum, the mass numbers, which corresponded to the

Scheme 5



Scheme 6



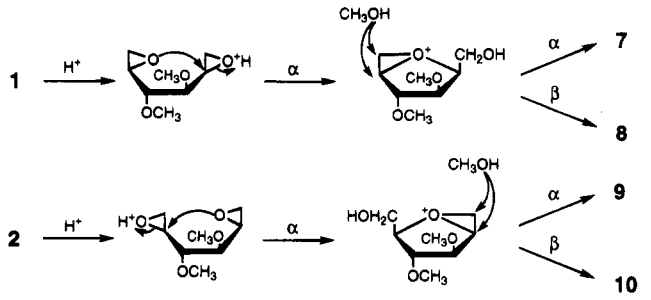
oligomers of the cyclic trimer to pentamer as the higher homologs of **6**, were only very slightly observed.

Discussion

The polymerizations of both **1** and **2** produced the same regio- and stereospecific polymer. Scheme 5 illustrates the proposed mechanism. The intramolecular cyclization proceeds through the ring opening of the first epoxide with inversion of the configuration by an S_N 2 attack of the second epoxide function on the α-carbon of the former oxonium ion (α-scission): the inversion of $R \rightarrow S$ for **1** and that of $S \rightarrow R$ for **2**. The ring opening of the second epoxide takes place at the β-carbon with retention of the configuration on the asymmetric carbon atoms, the carbon at which the attack is sterically favorable during the intermolecular propagation (β-scission): the retention of $R \rightarrow R$ for **1** and that of $S \rightarrow S$ for **2**. Therefore, polymer **3**, namely, poly[(1→6)-2,5-anhydro-3,4-di-*O*-methyl-D-glucitol], is produced by the cyclopolymerizations of **1** and **2** with a cationic initiator through a regio- and stereoselective mechanism.

The regio- and stereoselectivity of the cyclic constitutional units in the polymer obtained from the cyclopolymerizations of **1** and **2** should be related to that of the cyclic unimer from their cyclizations. Wiggins et al. reported that **1** and **2** were refluxed in water to produce only the 5-membered cyclic compound, 2,5-anhydro-3,4-di-*O*-methyl-D-glucitol (**3**) (Scheme 4). We examined the reactions of **1** and **2** in methanol containing a catalytic amount of hydrochloric acid as a unimolecular model cyclization for their cationic cyclopolymerizations, as shown in Scheme 6. From **1**, 2,5-anhydro-3,4,6-tri-*O*-methyl-D-glucitol (**7**) and 2,6-anhydro-3,4,5-tri-*O*-methyl-L-iditol (**8**) were obtained in 70 and 28% yield, respectively. On the other hand, for **2**, 2,5-anhydro-1,3,4-tri-*O*-methyl-D-glucitol (**9**) was isolated in 60% yield, **2** was recovered in 21% yield, and the mixture of compounds with m/z = 192 and 206 was obtained in 12% yield: the structure of the compound with m/z = 206 was estimated as 1,5-anhydro-2,3,4-tri-*O*-methyl-D-mannitol (**10**) from the ^{13}C NMR spectrum.

Scheme 7



These reactions can be explained by the Baldwin rules, which are the general ones for ring closure on the basis of the stereoelectronic effect.[7] A ring-forming process relating to epoxides is situated in the rules between the tetrahedral (Tet) and trigonal (Trig) systems, generally preferring Exo modes. The cyclizations of **1** and **2** are classified into the 5-Exo-Tet or 5-Exo-Trig types as the favored processes and the both types form 5-membered rings. For the intramolecular cyclizations of **1** and **2**, the ring opening of the protonated first epoxide, therefore, occurred at the α-carbon by attacking the second epoxide to form the 5-membered oxonium cation. Finally, methanol dominantly added to the less hindered β-carbon of the second epoxide to produce the 5-membered cyclic compounds, **7** and **9**, as the main products, while slightly adding to the more hindered α-carbon to produce the 6-membered cyclic compounds, **8** and **10**, as the minor ones, as shown in Scheme 7.

The regio- and stereoselectivity during the cyclizations of both **1** and **2** should be one reason for producing the polymer consisting of (1→6)-bonded 2,5-anhydro-D-glucitol recurring units for their cyclopolymerizations. However, small signals, which were observed in the ^{13}C NMR spectra of both polymers (Figure 2), indicate that the polymers should slightly contain the 6-membered cyclic repeating units, such as 2,6-anhydro-D-glucitols **8** and **10** corresponding to the possible cyclic units of **II** and **III**, except for 2,5-anhydro-D-mannitol as the main structural unit.

The cationic polymerizability of **1** was higher than that of **2** in terms of the M_n and yield for the resulting polymer. The difference in the reactivity should be caused by participation of the stereochemistry of the intramolecular cyclized oxonium cations. However, we cannot discuss this problem in detail and need to further study the semiempirical calculation for the intermediate state.

For some polymerizations of **1** and **2**, the bicyclic unimer **5** and the cyclic dimer of 2,5-anhydro-3,4-di-*O*-methyl-D-glucitol **6** and its higher homologs were formed together with the *n*-hexane-insoluble polymers. These cyclic compounds should be formed by the back-biting of the growing chain end through oxonium cation exchange and/or specific oligomerization. This is an unresolved matter and further elucidation is needed in terms of the kinetic study. However, the cyclic dimer **6** is a chiral 12-crown-4 and this oligomerization is interesting for the synthesis of chiral crown ethers.

Conclusions

The cationic cyclopolymerizations of 1,2:5,6-dianhydro-3,4-di-*O*-methyl-D-mannitol (**1**) and -L-iditol (**2**) were regio- and stereoselective and produced the same polymer structure, poly[(1→6)-2,5-anhydro-3,4-di-*O*-methyl-D-glucitol]. After separating the *n*-hexane-insoluble polymers for the polymerization using $BF_3{\cdot}OEt_2$, 1,6:

2,5-dianhydro-3,4-di-*O*-methyl-D-glucitol and the cyclic dimer of 2,5-anhydro-3,4-di-*O*-methyl-D-glucitol were isolated as the *n*-hexane-soluble products. In addition, the higher cyclic homologs were observed in the mass spectrum of the *n*-hexane-soluble part.

References and Notes

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