Synthesis of Hyperbranched Polytetritol by Ring-Opening Multibranching Polymerizations of 2,3-Anhydroerythritol and 2,3-Anhydro-DL-threitol

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ABSTRACT: 2,3-Anhydroerythritol (**1a**) and 2,3-anhydro-DL-threitol (**1b**) were polymerized using boron trifluoride diethyl etherate ($BF_3 \cdot OEt_2$) as a cationic initiator. The polymerizations of **1a** and **1b** proceeded through a ring-opening reaction with a proton-transfer reaction to produce hyperbranched carbohydrate polymers (**2a** and **2b**) consisting of DL-threitol and erythritol units, respectively. The degrees of branching (DBs) estimated by the ^{13}C NMR spectra of **2a** and **2b** were 0.47 and 0.45, respectively. The weight-average molecular weight ($M_{w,SLS}$) values (2.67×10^5−3.20×10^6) estimated using static light scattering (SLS) of the resulting hyperbranched carbohydrate polymers were significantly higher than the weight-average molecular weight ($M_{w,SEC}$) values (1.04×10^3−2.77×10^3) estimated using size exclusion chromatography (SEC). The viscosities of **2a** and **2b** in aqueous sodium nitrate ($NaNO_3$) solution were very low, and the intrinsic viscosities ([η]) of **2a** and **2b** were in the range from 0.0190 to 0.0250 dL g^{-1}. The three-dimensional properties characterized by the SLS and viscosity measurements indicated that **2a** and **2b** should be spherical molecules.

Introduction

Ring-opening multibranching polymerization of cyclic monomers is a versatile method for synthesizing hyperbranched macromolecular architectures. Since Suzuki et al. first reported the ring-opening multibranching polymerization using a cyclic carbamate,[1a,b] there have been were various studies using cyclic monomers, such as oxetanes,[2a−d] tetrahydrofurans,[3] lactones,[4a,b] and oxiranes.[5a−e] In particular, glycidol is the simplest, commercially available, and cheap oxirane, so that many efforts to prepare hyperbranched polyglycerol have been carried out; for example, Penczek and Dworak et al. reported the synthesis of a highly branched polymer by the cationic polymerization of glycidol.[5a,b] In addition, Frey et al. reported the anionic ring-opening multibranching polymerization of glycidol and used the resulting hyperbranched polyglycerol as the molecular nanocapsules for hydrophilic guests.[5c−e] Thus, for the ring-opening multibranching polymerization using cyclic monomers, the design and synthesis of hyperbranched polymers with novel structures together with their application is of significant interest.

Previously, we proposed a hyperbranched carbohydrate polymer as a novel class of polysaccharides, which was based on the synthetic strategy of the ring-opening multibranching polymerization of anhydro sugars as cyclic monomers, such as 1,2:5,6-dianhydro-D-mannitol,[6] 1,6-anhydro-β-D-mannopyranose,[7a,b] 1,6-anhydro-β-D-glucopyranose,[7b] and 1,6-anhydro-β-D-galactopyranose.[7b] The resulting hyperbranched carbohydrate polymers exhibited characteristic properties due to their spherical and compact structure, e.g., a high water solubility and extremely low solution viscosity, which significantly differed from those of linear carbohydrate polymers. To expand the family of hyperbranched carbohydrate polymers, it is important to elucidate applicable anhydro sugar monomers for the ring-opening multibranching polymerization. Recently, we reported the synthesis of hyperbranched polytetritol by the ring-opening multibranching polymerization of 1,4-anhydroerythritol (**3a**) and 1,4-anhydro-L-threitol (**3b**).[3] Although these monomers were successfully polymerized using superacids, such as trifluoromethanesulfonic acid and fluorosulfonic acid, as the cationic initiator, the resulting hyperbranched polytetritol contained the 1,4-anhydrotetritol unit as an unexpected unit. Our continuous interest is to expand the family of hyperbranched carbohydrate polymers along with their characteristic properties due to their spherical and compact structure, so that it is important to synthesize and characterize hyperbranched polytetritol without any anhydrotetritol unit. Thus, we now report the synthesis of a hyperbranched carbohydrate polymer (**3a, 3b**) essentially consisting of tetritol units by the ring-opening multibranching polymerization using 2,3-anhydroerythritol (**1a**) and 2,3-anhydro-DL-threitol (**1b**), which are the structural isomers of 1,4-anhydrotetritol, as shown in Scheme 1. The structures of **2a** and **2b** are characterized using the results based on the NMR, static light scattering, and solution viscosity measurements by the comparison with a linear polymer of (2→3)-erythritol (**4**) along with hyperbranched polytetritol prepared from **3a** and **3b**. In

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Scheme 1

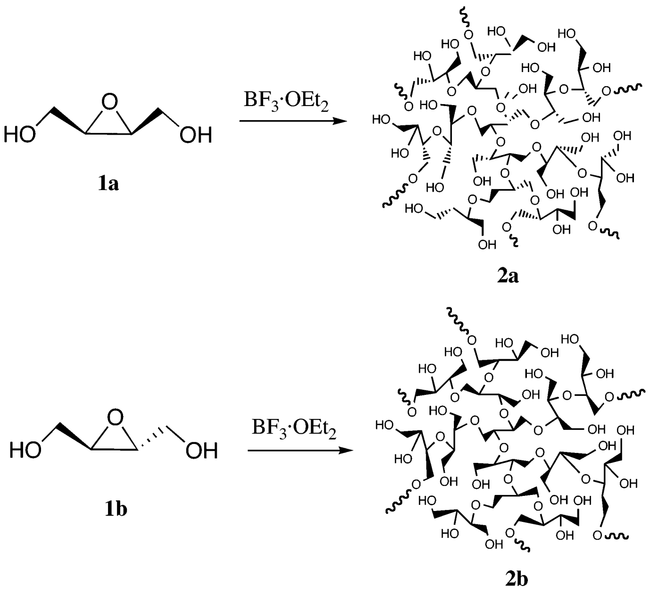
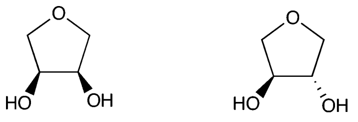


Chart 1



addition, the polymerization mechanisms of **1a** and **1b** are discussed on the basis of the structures and the degrees of branching (DBs) of the resulting hyperbranched poly-DL-threitol (**2a**) and hyperbranched polyerythritol (**2b**).

Experimental Section

Measurements. The ^{1}H (400 MHz) and ^{13}C NMR spectra (100 MHz) were recorded using a JEOL JNM-A400II instrument. The quantitative ^{13}C NMR spectra were obtained using a 20% (w/v) sample in deuterium oxide (D_2O) at 25 °C, 45° pulse angle, inverse gated decoupling with a 7.0 s delay, 6000 scans, and acetone as the internal reference. Size exclusion chromatography (SEC) for the water-soluble polymer was performed in aqueous sodium nitrate ($NaNO_3$) solution (0.2 mol L^{-1}) at 40 °C (1.0 mL min^{-1}) using a TOSOH HPLC system (HLC-8020) equipped with two TSK_{gel} $GMPW_{XL}$ columns (pore size, 12.5−100 nm; bead size, 13 μm; exclusion limit, 5×10^7) and a refractive index detector. The weight-average molecular weights ($M_{w,SEC}$) and the molecular weight distributions (M_w/M_n) of the polymer samples were calculated on the basis of poly(ethylene glycol) calibrations. For the organic solvent-soluble polymer, the SEC measurement was performed at 40 °C in chloroform (0.8 mL min^{-1}) using a Jasco GPC-900 system equipped with a TOSOH TSK_{gel} GMH_{HR}-M column (linear, 7.8 mm × 300 mm; pore size, 16 nm; bead size, 5 μm; exclusion limit, 4×10^6), a Shodex KF-804L column (linear, 8 mm × 300 mm; pore size, 20 nm; bead size, 7 μm; exclusion limit, 4×10^5), and a refractive index detector. The $M_{w,SEC}$ and the M_w/M_n were calculated on the basis of a polystyrene calibration. The preparative SEC was performed in chloroform (3.8 mL min^{-1}) at 23 °C using a JAI LC-908 equipped with JAI JAIGEL-2H polystyrene column (pore size, 40−50 Å; bead size, 15 μm; exclusion limit, 5×10^3), a JAIGEL-2.5H polystyrene column (pore size, 60−70 Å; bead size, 16.5 μm; exclusion limit, 2×10^4), and JAI UV-310 and JAI RI-5HC detectors. A static light scattering (SLS) measurement was performed in an aqueous $NaNO_3$ solution (0.2 mol L^{-1}) or toluene at 40 °C using an Otsuka Electronics CALLS-1000 light scattering spectrometer (λ = 632.8 nm). The refractive index increment (dn/dc) was measured in aqueous $NaNO_3$ solution (0.2 mol L^{-1}) or toluene using an Otsuka Electronics DRM-1021 double-beam differential refractometer. The intrinsic viscosity ([η]) was determined in aqueous $NaNO_3$ solution (0.2 mol L^{-1}) at 40 °C using a Canon-Fenske viscometer after the sample solution was filtered.

Materials. *cis*-2-Butene-1,4-diol (Tokyo Kasei Co., >94%), 2-butyne-1,4-diol (Kanto Kagaku Co., 97%), *N*,*N*-dimethylformamide (DMF) (Junsei Chem. Co., 99.0%), anhydrous magnesium sulfate (Junsei Chem. Co., 99.5%), methanol (Junsei Chem. Co., 99.6%), acetone (Junsei Chem. Co., 99.0%), chloroform (Junsei Chem. Co., 98.0%), allyl bromide (Kanto Kagaku Co., 99.0%), ethyl alcohol (Japan Alcohol Trading Co., 99.0%), and silver oxide (Ag_2O) (Aldrich, 99.0%) were used without further purifications. Boron trifluoride diethyl etherate ($BF_3 \cdot OEt_2$) (Kanto Kagaku Co., 95.0%) was purified by distillation under reduced pressure. The dialysis membranes (Spectra/Por6 regenerated cellulose, MWCO 1000, and Spectra/Por cellulose ester MWCO 500) were purchased from Spectrum Laboratories, Inc. 2,3-Anhydroerythritol (**1a**) and 2,3-anhydro-DL-threitol (**1b**) were synthesized from *cis*-2-butene-1,4-diol and *trans*-2-butene-1,4-diol,[8] respectively, according to the methods from a previous report.[9a,b]

Synthesis of 2,3-Anhydro-1,4-di-*O*-allylerythritol (5). To a solution of 2,3-anhydroerythritol (3.33 g, 31.7 mmol) in DMF (50 mL) were added silver oxide (20.0 g, 86.3 mmol) and allyl bromide (10.0 mL, 116 mmol) at 40 °C. The reaction mixture was stirred at 40 °C for 4 h. The suspension was cooled, and the salts were filtered off and washed with acetone. The filtrates were evaporated under reduced pressure. The residue was purified by column chromatography on silica gel with hexane/ethyl acetate (10:1 v/v) and distilled under reduced pressure to give a colorless liquid **5** (2.2 g) in a 37.4% yield; bp 141 °C/33 mmHg; R_f 0.29. ^{1}H NMR ($CDCl_3$): δ = 5.91−5.81 (m, allyl, −CH= , 2H), 5.24 (ddd, $^3J_{trans}$ = 17.3 Hz, J_{gem} = 3.2 Hz, ^4J = 1.7 Hz, allyl trans =CH_2, 2H), 5.16 (ddd, $^3J_{cis}$ = 10.5 Hz, J_{gem} = 3.2 Hz, ^4J = 1.2 Hz, allyl, cis = CH_2, 2H), 4.06−3.93 (m, allyl, −CH_2−, 4H), 3.64 (dd, J_{gem} = 17.3 Hz, J_{vic} = 3.4 Hz, CH_2, H-1 and H-4, 2H), 3.49−3.46 (m, CH_2, H-1 and H-4, 2H), 3.20−3.16 ppm (m, epoxy, CH, H-2 and H-3, 2H). ^{13}C NMR ($CDCl_3$): δ = 134.29 (allyl, −CH=), 117.43 (allyl, =CH_2), 72.14 (allyl, −CH_2−), 68.03 (CH_2), 54.38 ppm (CH). Anal. Calcd for $C_{10}H_{16}O_3$ (184.2): C, 65.19; H, 8.75. Found: C, 64.99; H, 8.78. FI-MS: *m/z* (relative intensity): 184 (M^+, 100), 185 (MH^+, 79.4).

Polymerization of 5. All procedures were performed under an argon atmosphere. The monomer **5** (1.00 g, 5.43 mmol) was placed in an ampule and dried under reduced pressure for 18 h. After adding $BF_3 \cdot OEt_2$ (34.4 μL, 0.271 mmol), the ampule was sealed and cooled at 0 °C for 240 h. The polymerization mixture was quenched by adding water (5 mL) and then neutralized with aqueous ammonium solution. The mixture was extracted three times with chloroform, dried with anhydrous magnesium sulfate, filtered, and evaporated. The residue was dissolved in chloroform (1 mL). A part of the solution (0.2 mL) was applied to the preparative SEC, and then the eluents with the retention times of 30−45 min were fractionated. This procedure was repeated five times. The combined fractions were evaporated and then dried in vacuo to give (2→3)-1,4-di-*O*-allyl-DL-threitol (**6**) (0.720 g) in a 72.0% yield. The $M_{w,SEC}$ and M_w/M_n values were 1800 and 1.40, respectively. ^{1}H NMR ($CDCl_3$): δ = 5.87−5.60 (m, allyl, −CH=, 2H), 5.25 (d, J_{vis} = 17.1 Hz, allyl, trans =CH_2, 2H), 5.25−4.84 (m, allyl, =CH_2, 2H), 3.94−3.75 (m, allyl, −CH_2−, 4H), 3.73−3.01 (m, CH and CH_2, 6H). ^{13}C NMR ($CDCl_3$): δ = 134.68 (allyl, −CH=), 116.11 (allyl, =CH_2), 77.48 (C2 and C3), 71.78 (allyl, −CH_2−), 69.29 ppm (C1 and C4).

Isomerization of 6. To a solution of **6** (0.430 g) in toluene (70 mL), ethanol (160 mL), and water (2 mL) was added tris(triphenylphosphine)chlororhodium ($RhCl(PPh_3)_3$) (0.364 g, 0.393 mmol) and 1,4-diazabicyclo[2.2.2]octane (DABCO) (0.130 g, 1.16 mmol). After the reaction mixture was refluxed for 12 h, it was cooled to room temperature, and the solvent was evaporated. The residue was purified by the preparative SEC as well as **6**. The combined fractions were evaporated and then

Table 1. Polymerization of 2,3-Anhydrotetritol (1a and 1b) Using Borontrifluoride Diether Etherate

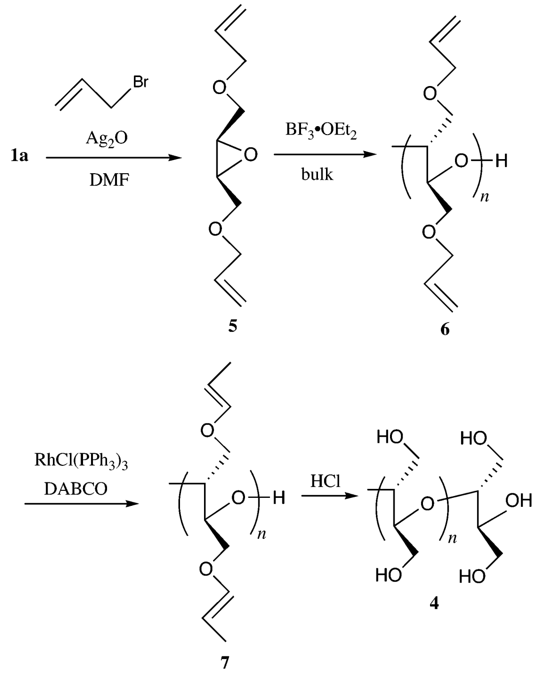
run	monomer	[M]/[I]	temp/°C	time/h	yield/%	$M_{\mathrm{w,SEC}}$ $(M_\mathrm{w}/M_\mathrm{n})^a$	$M_{\mathrm{w,SLS}}{}^b \times 10^{-5}$	$[\eta]^c \times 10^{-2}$/dL g^{-1}	DB^d
1	**1a**	100	80	120	44.8	1040 (2.32)	2.67	1.90	0.47
2	**1a**	100	100	60	41.2	1310 (1.87)	3.38	1.99	0.47
3	**1a**	100	100	100	57.3	1770 (1.99)	16.1	2.30	0.47
4	**1a**	100	100	120	60.8	2170 (2.98)	31.2	2.48	0.47
5	**1a**	200	100	120	51.8	2770 (2.45)	32.0	2.50	0.47
6	**1b**	100	100	120	61.4	2400 (2.55)	30.8	2.42	0.45

[a] Measured in an aqueous $NaNO_3$ solution (0.2 mol L^{-1}) using poly(ethylene glycol) as standards. [b] Measured in an aqueous $NaNO_3$ solution (0.2 mol L^{-1}). [c] Obtained from Canon-Fenske viscometer in an aqueous $NaNO_3$ solution (0.2 mol L^{-1}). [d] Determined from ^{13}C NMR spectra.

dried in vacuo to give (2→3)-1,4-di-*O*-2-propenyl-DL-threitol (**7**) (0.380 g) in a 88.4% yield.

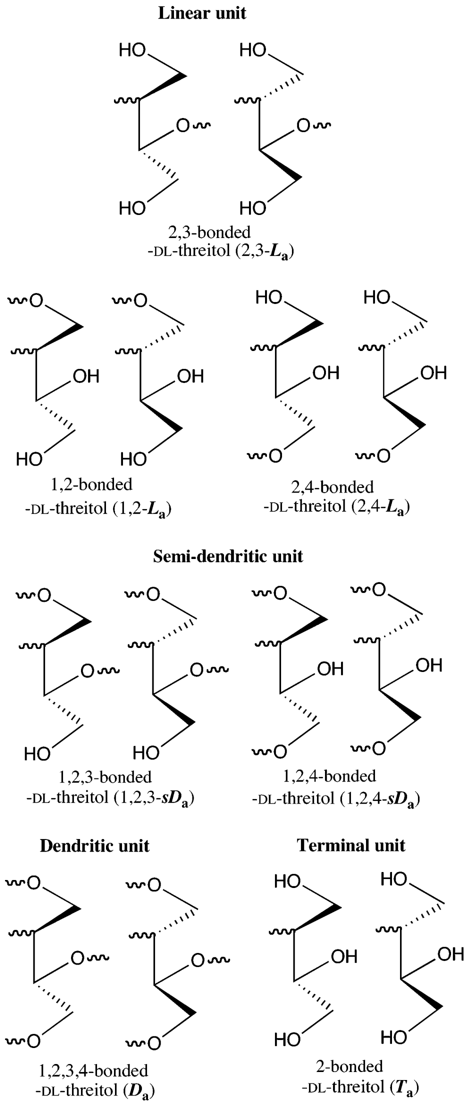
Hydrolysis of 7. To a solution of **7** (380 mg) in acetone (180 mL) was added a 0.5 mol L^{-1} aqueous HCl solution (6 mL), and the mixture was heated under reflux for 15 min. The mixture was evaporated, and the residue was purified using a dialysis membrane (MWCO 500) in water. After dialysis, the residue was freeze-dried to give a white solid of (2→3)-DL-threitol (**4**) (85.0 mg) in a 39.6% yield. The $M_{\mathrm{w,SEC}}$ and $M_\mathrm{w}/M_\mathrm{n}$ values were 890 and 1.22, respectively, and the $M_{\mathrm{w,SLS}}$ value was 1.08×10^3 (d*n*/d*c* = -5.91×10^{-1}). ^{1}H NMR (D_2O) δ: 4.14−3.37 ppm (broad). ^{13}C NMR (D_2O) δ: 81.81 (C2 for the terminal unit), 79.72 (C2 and C3 for the repeating unit), 76.34 (CH_2), 71.93 (C3 for the terminal unit), 67.43 (CH_2), 62.84 (C4 for the terminal unit), 60.99 ppm (C1 and C4 for the repeating unit and C1 for the terminal unit).

Scheme 2



Typical Procedure for Polymerization of 2,3-Anhydroerythritol (1a). All procedures were performed under an argon atmosphere. Monomer **1a** (1.00 g, 9.61 mmol) was placed in an ampule and dried under reduced pressure for 18 h. The ampule was heated at 100 °C, and then $BF_3 \cdot OEt_2$ (12.2 μL, 9.61×10^{-2} mmol) was added. After 120 h, the polymerization mixture was quenched by adding water (5 mL), then neutralized with an aqueous ammonia solution, and evaporated. The residue was dissolved in methanol (1 mL) and then poured into a large volume of acetone. The precipitated polymer was filtered off, and the filtrate was purified using a dialysis membrane (MWCO 500) in water. After dialysis, the residue was freeze-dried to give the polymer of **2a** (0.608 g) in a 60.8% yield. The $M_{\mathrm{w,SEC}}$ and $M_\mathrm{w}/M_\mathrm{n}$ values were 2.17×10^3 and 2.98, respectively, and the $M_{\mathrm{w,SLS}}$ value was 3.12×10^6 (d*n*/d*c* = 1.40×10^{-1}). ^{1}H NMR (D_2O) δ: 4.41−4.33 (m), 4.06−3.89 (m), 3.85−3.69 (m, H-3 for 2-bonded DL-threitol ($\boldsymbol{T}_\mathbf{a}$) as the terminal unit), 3.68−3.52 (m), 3.50−3.37 ppm (m, H-2 for $\boldsymbol{T}_\mathbf{a}$). ^{13}C NMR ($D_2O$) δ: 85.61 (CH), 81.76 (C2 for $\boldsymbol{T}_\mathbf{a}$), 81.20−80.45 ($CH_2$), 80.24 (C2 and C3 for 2,3-bonded-DL-threitol (2,3-$\boldsymbol{L}_\mathbf{a}$) as the linear unit), 75.64 (CH), 74.32 (CH), 73.60 (CH_2), 72.98−72.81 (CH), 72.34 (C3 for $\boldsymbol{T}_\mathbf{a}$), 71.18 ($CH_2$), 71.15−69.55 (CH), 69.42−67.61 (CH_2), 63.40 (C4 for $\boldsymbol{T}_\mathbf{a}$), 62.00−61.13 ($CH_2$), and 60.44 ppm (C1 for $\boldsymbol{T}_\mathbf{a}$ and C1 and C4 for 2,3-$\boldsymbol{L}_\mathbf{a}$).

Chart 2



2,3-bonded -DL-threitol (2,3-$\boldsymbol{L}_\mathbf{a}$)

1,2-bonded -DL-threitol (1,2-$\boldsymbol{L}_\mathbf{a}$)

2,4-bonded -DL-threitol (2,4-$\boldsymbol{L}_\mathbf{a}$)

1,2,3-bonded -DL-threitol (1,2,3-$\boldsymbol{sD}_\mathbf{a}$)

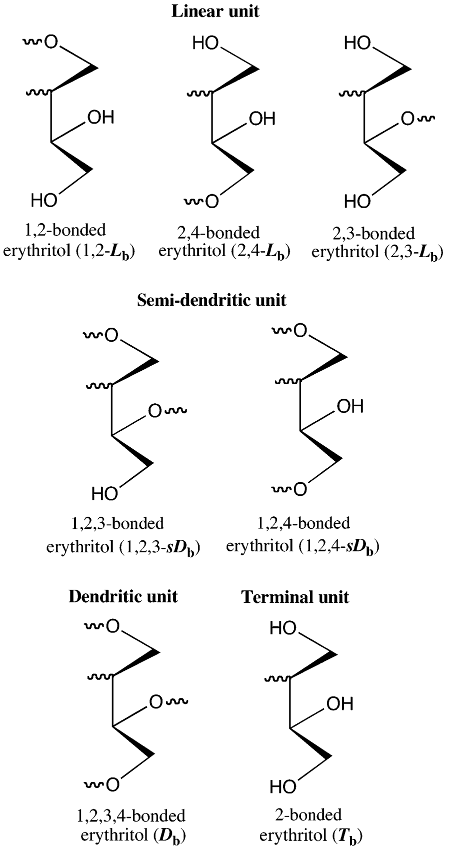
1,2,4-bonded -DL-threitol (1,2,4-$\boldsymbol{sD}_\mathbf{a}$)

1,2,3,4-bonded -DL-threitol ($\boldsymbol{D}_\mathbf{a}$)

2-bonded -DL-threitol ($\boldsymbol{T}_\mathbf{a}$)

Procedure for Polymerization of 2,3-Anhydro-DL-threitol (1b). All procedures were performed under an argon atmosphere. Monomer **1b** (1.00 g, 9.61 mmol) was placed in an ampule and dried under reduced pressure for 18 h. The ampule was heated at 100 °C, and then $BF_3 \cdot OEt_2$ (12.2 μL, 9.61×10^{-2} mmol) was added. After 120 h, the polymerization mixture was quenched by adding water (5 mL), neutralized with an aqueous ammonium solution, and then evaporated. The residue was dissolved in methanol (1 mL) and then poured into a large amount of acetone. The precipitated polymer was filtered off, and the filtrate was purified using a dialysis membrane (MWCO 500) in water. After dialysis, the residue was freeze-dried to give the polymer of **2b** (0.614 g) in a 61.4% yield. The $M_{\mathrm{w,SEC}}$ and $M_\mathrm{w}/M_\mathrm{n}$ values were 2.40×10^3 and 2.55, respectively, and the $M_{\mathrm{w,SLS}}$ value was 3.08×10^6 ($\mathrm{d}n/\mathrm{d}c = 1.04 \times 10^{-1}$). ^{1}H NMR ($D_2O$) δ: 4.46–4.34 (m), 4.22–4.20 (m, H2 and H3 for 2,3-bonded erythritol (2,3-$\boldsymbol{L}_\mathbf{b}$) as the linear unit, 2H), 4.09–3.65 (m), 3.52–3.31 ppm (m, H2 for 2-bonded erythritol ($\boldsymbol{T}_\mathbf{b}$) as the terminal unit). ^{13}C NMR (D_2O) δ: 83.01 (C2 for $\boldsymbol{T}_\mathbf{b}$), 81.80 (C2 and C3 for $\boldsymbol{D}_\mathbf{b}$), 81.49 (C2 and C3 for 2,3-$\boldsymbol{L}_\mathbf{b}$), 76.88 (CH), 74.94 (CH), 74.24 (CH_2), 74.01 (CH), 73.38 (CH), 73.00 (CH_2), 72.69 (C3 for $\boldsymbol{T}_\mathbf{b}$), 71.98 (CH), 71.64 (CH), 71.27 (C1 and C4 for $\boldsymbol{D}_\mathbf{b}$), 70.89 (CH), 70.44–69.29 (CH_2), 65.85 (CH_2), 64.77 (C4 for $\boldsymbol{T}_\mathbf{b}$), 64.31 ($CH_2$), and 60.11 ppm (C1 and C4 for 2,3-$\boldsymbol{L}_\mathbf{b}$, and C1 for $\boldsymbol{T}_\mathbf{b}$).

Chart 3



Degree of Branching (DB). The DBs of **2a** and **2b** prepared from the AB_3 monomer were determined from the ratio of the terminal units using Frey's equation.[3,6,10] In the ^{13}C NMR spectrum of **2a**, the signal at 72.34 ppm was assigned to the C3 methyne carbon due to the 2-bonded DL-threitol ($\boldsymbol{T}_\mathbf{a}$) as the terminal unit. The ratio of $\boldsymbol{T}_\mathbf{a}$, $\boldsymbol{T}_\mathbf{a}/(\boldsymbol{D}_\mathbf{a} + \boldsymbol{sD}_\mathbf{a} + \boldsymbol{L}_\mathbf{a} + \boldsymbol{T}_\mathbf{a})$, was estimated from the integrated area of the methyne carbon peaks as [2 × (the integrated area of C3 methyne peak for $\boldsymbol{T}_\mathbf{a}$)/(the integrated area of total methyne peaks)]. The DB of polymer **2a** was calculated as shown in eq 1.

$$\mathrm{DB} = \frac{3}{2}\left|\frac{\boldsymbol{T}_\mathbf{a}}{\boldsymbol{D}_\mathbf{a} + \boldsymbol{sD}_\mathbf{a} + \boldsymbol{L}_{a} + \boldsymbol{T}_\mathbf{a}}\right| \qquad (1)$$

This calculation method was applied to **2b**. From the ratio of the 2-bonded erythritol ($\boldsymbol{T}_\mathbf{b}$) as the terminal unit, which was estimated from the signal at 72.69 ppm in the ^{13}C NMR spectrum, the DB of **2b** was calculated.

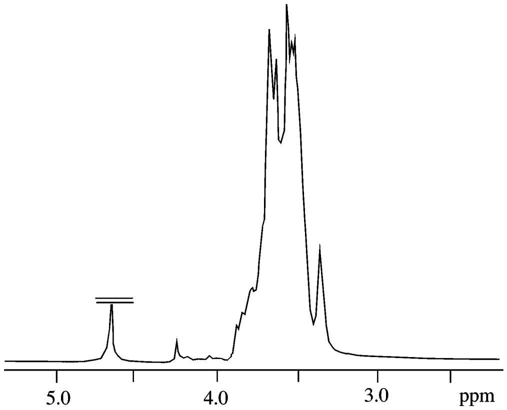


Figure 1. ^{1}H NMR spectrum of **2a** (run 4).

Results and Discussion

Polymerization. The bulk polymerization of 2,3-anhydroerythritol (**1a**) and 2,3-anhydro-DL-threitol (**1b**) was carried out using boron trifluoride diethyl etherate ($BF_3 \cdot OEt_2$) as the initiator at 80 or 100 °C. After the initiator was added to the monomer, the viscosity of the polymerization system immediately increased. The polymeric products were isolated by reprecipitation using methanol and acetone. The resulting polymers were white solids, which were soluble in water, sparingly soluble in methanol, and insoluble in other organic solvents. Table 1 summarizes the polymerization results. For the polymerization of **1a**, the weight-average molecular weight values ($M_{\mathrm{w,SLS}}$) measured by the static light scattering (SLS) and the yield of the resulting polymer increased with the rising the polymerization temperature; i.e., when the [**1a**]/[$BF_3 \cdot OEt_2$] molar ratio of 100 was used for 120 h, the $M_{\mathrm{w,SLS}}$ value was 2.67×10^5 in 44.8% yield at 80 °C (run 1) and 1.61×10^6 in 57.3% yield at 100 °C (run 3). The $M_{\mathrm{w,SLS}}$ value and yield also increased with the extension of the polymerization time (runs 2, 3, and 4). For the polymerization of **1b** at 100 °C for 120 h, the $M_{\mathrm{w,SLS}}$ values were 3.08×10^6 in 61.4% yield in the [**1b**]/[$BF_3 \cdot OEt_2$] molar ratio of 100. The $M_{\mathrm{w,SLS}}$ values (2.67×10^5–3.20×10^6) of the resulting polymers were higher than those (1.00×10^4–5.10×10^5) of the hyperbranched polytetritols prepared by the ring-opening multibranching polymerizations of 1,4-anhydroerythritol (**3a**) and 1,4-anhydro-L-threitol (**3b**).[3]

Polymer Structure and Degree of Branching. In the ^{1}H NMR spectrum of the polymer obtained from **1a**, the characteristic absorption at 3.25–3.35 ppm due to the epoxy proton of **1a** disappeared, as shown in Figure 1, indicating that the epoxy group in **1a** was consumed. Thus, the polymer obtained from **1a** should consist of 14 kinds of DL-threitol repeating units (Chart 2). To investigate the polymer structure, the ^{13}C NMR spectrum of the polymer was compared with that of a linear carbohydrate polymer of (2→3)-DL-threitol (**4**) as shown in Figure 2. For the ^{13}C NMR spectrum of **4**, the major signals marked by the open circles at 79.72 and 60.99 ppm were assigned to the C2,3 and C1,4 carbons for the 2,3-bonded DL-threitol repeating unit, respectively. In the comparison with the chemical shifts of L-threitol as the model compound,[3] the small signals marked by the closed circles at 81.81, 71.93, 62.84, and 60.99 ppm were assigned to the C2, C3, C4, and C1 carbons for the 2-bonded DL-threitol unit as the polymer terminals, respectively. On the other hand, the ^{13}C NMR spectrum

3of the polymer obtained from **1a** consisted of a number of split and broad signals. Some signals correspond to those of **4**; e.g., the major signals marked by the open squares at 81.76, 72.34, 63.44, and 60.44 ppm agreed with the chemical shifts of the signal for the 2-bonded DL-threitol terminal unit. The small signals marked by the closed squares at 80.24 and 60.44 ppm agreed with the chemical shifts of the signal for the 2,3-bonded DL-threitol repeating unit of **4**. In addition, by comparison with the hyperbranched poly-L-threitol prepared from **3b**, the remaining signals could be assigned to the 1,2-bonded DL-threitol (1,2-$\boldsymbol{L}_\mathrm{a}$) as the linear unit, 1,2,3- and 1,2,4-bonded-DL-threitol (1,2,3-$\boldsymbol{sD}_\mathrm{a}$ and 1,2,4- $\boldsymbol{sD}_\mathrm{a}$) as the semi-dendritic unit, and 1,2,3,4-bonded-DL-threitol (1,2,3,4-$\boldsymbol{D}_\mathrm{a}$) as the dendritic unit. Thus, the polymer obtained from **1a** was a hyperbranched poly-DL-threitol (**2a**) containing numerous 2-bonded DL-threitols ($\boldsymbol{T}_\mathrm{a}$) as the terminal units.

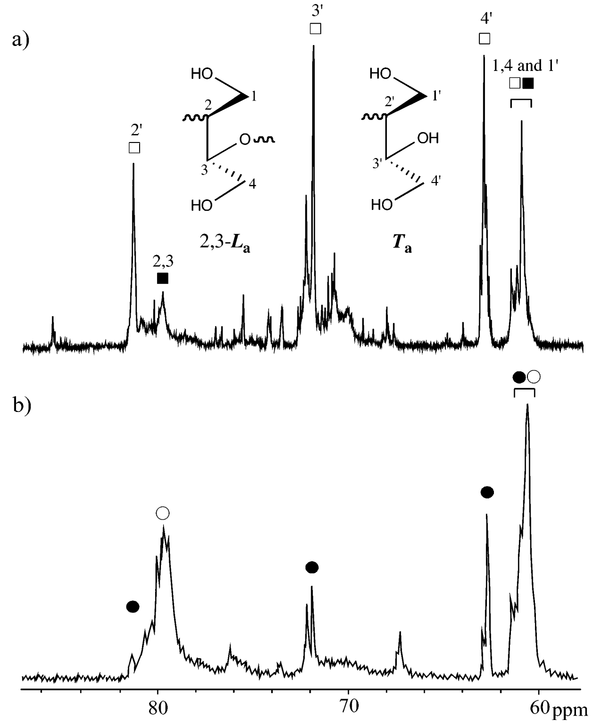


Figure 2. ^{13}C NMR spectra of (a) **2a** (run 4) and (b) (2→3)-DL-threitol (**3**).

For the polymer obtained from **1b**, the ^{1}H NMR and ^{13}C NMR spectra are shown in Figure 3. In the ^{1}H NMR spectrum, the signal was broad and the characteristic absorption at 3.25−3.35 ppm due to the epoxy proton of **1b** disappeared, so that the polymer obtained from **1b** should consist of 7 kinds of erythritol repeating units as shown in Chart 3. The ^{13}C NMR spectrum consisted of a number of split and broad signals. In the comparison with the chemical shifts of erythritol as the model compound, the major signals marked by the open triangles at 83.01, 72.69, 64.77, and 60.11 ppm were assigned to the carbon for the 2-bonded erythritol ($\boldsymbol{T}_\mathrm{b}$) as the terminal unit.[3] The shape of the ^{13}C NMR spectrum of the polymer obtained from **1b** was similar to that of **2a**, so that the signals marked by the closed triangles at 81.49 and 60.11 ppm should be assigned to the carbon for the 2,3-bonded erythritol (2,3-$\boldsymbol{L}_\mathrm{b}$) as the linear unit. By comparison with the hyperbranched polyerythritol prepared from **3b**,[3] the rest of the signals could be assigned to 1,2-bonded erythritol (1,2-$\boldsymbol{L}_\mathrm{b}$) as the linear unit, 1,2,3- and 1,2,4-bonded erythritol (1,2,3- and 1,2,4-$\boldsymbol{sD}_\mathrm{b}$), and 1,2,3,4-bonded erythritol ($\boldsymbol{D}_\mathrm{b}$) as the dendritic unit. For example, the signals marked by the open diamonds at 81.80 and 71.27 ppm were assigned to the carbon for $\boldsymbol{D}_\mathrm{b}$. These results indicated that the polymer obtained from **1b** should be a hyperbranched polyerythritol (**2b**) having numerous erythritol terminal units.

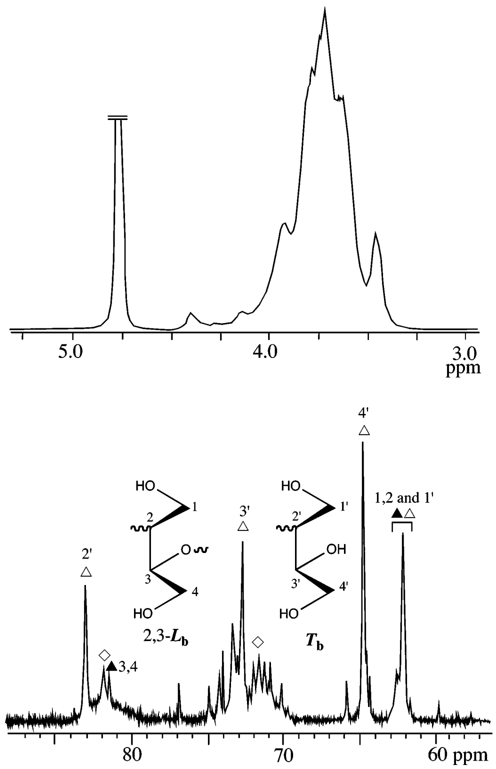


Figure 3. (a) ^{1}H NMR and (b) ^{13}C NMR spectra of **2b**.

Because the ring strains of the oxirane-type monomers of **1a** and **1b** were larger than the tetrahydrofuran-type monomers of **3a** and **3b**, **2a** and **2b** were hyperbranched polytetritols without the 2,3-anhydroerythritol and 2,3-anhydro-L-threitol units as the anhydrotetritol units,[11] though the hyperbranched polytetritol prepared from **3a** and **3b** contained 1,4-anhydroerythritol and 1,4-anhydro-L-threitol as the anhydrotetritol units.[3]

Monomers **1a** and **1b** have an epoxy and two hydroxy groups in a molecule, so that they are classified as latent AB$_3$-type monomers. The degrees of branching (DBs) prepared from the AB$_3$-type monomers were determined from the ratio of the terminal unit using Frey's equation, as shown in the Experimental Section.[10] The ratio of the terminal unit in **2a**, $\boldsymbol{T}_\mathrm{a}/(\boldsymbol{D}_\mathrm{a} + \boldsymbol{sD}_\mathrm{a} + \boldsymbol{L}_a + \boldsymbol{T}_\mathrm{a})$, which was estimated from the ^{13}C NMR measurement, was 31.0%. Thus, the DB of **2a** was determined to be 0.47, as summarized in Table 1. For polymer **2b**, the ratio of the terminal unit, $\boldsymbol{T}_\mathrm{b}/(\boldsymbol{D}_\mathrm{b} + \boldsymbol{sD}_\mathrm{b} + \boldsymbol{L}_b + \boldsymbol{T}_\mathrm{b})$, was 30.0%, and the DB was 0.45. Although the DBs of hyperbranched carbohydrate polymer prepared from **3a** and **3b** varied in the range of 0.22−0.46, the DBs did not change according to the polymerization condition.[3]

Three-Dimensional Property. In general, highly branched polymers, such as dendrimers, star polymers, and hyperbranched polymer, are known to have spherical conformations in solution.[12a,b,13] Thus, the $M_{\mathrm{w,SLS}}$ values were smaller than the weight-average molecular weight ($M_{w,SEC}$) values estimated using size exclusion chromatography (SEC); i.e., the $M_{w,SLS}$ values ($2.67 \times 10^5-3.20 \times 10^6$) were ca. $2.57 \times 10^2-1.44 \times 10^3$ times larger than the $M_{w,SEC}$ values ($1.04 \times 10^3-2.77 \times 10^3$). On the contrary, for the linear polymer (2→3)-DL-threitol, the $M_{w,SLS}$ value of 1080 was somewhat larger than the $M_{w,SEC}$ value of 890. For the solution viscosity, a linear dependence between the reduced viscosity and the polymer concentration was observed, as shown in Figure 4, indicating that no aggregation occurred for **2a** and **2b** in an aqueous $NaNO_3$ solution (0.2 mol L^{-1}). Therefore, the measured $M_{w,SLS}$ values should correspond to the absolute molecular weights. The solution viscosity of **2a** and **2b** was extremely low, and the intrinsic viscosity ([η]) was in the range of 0.019−0.025 dL g^{-1}, as listed in Table 1.

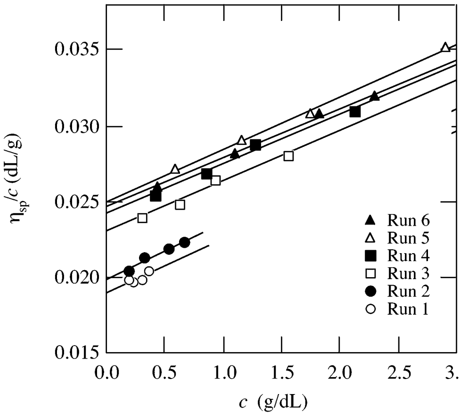


Figure 4. Viscosity vs concentration plots for **2a** and **2b**.

The relationship between [η] and the molecular weight (M) can be described by the Mark−Houwink equation of $[\eta] = KM^a$. Figure 5 shows the double-logarithmic plots of $[\eta]-M_{w,SLS}$. The value of the slope, which is a in the Mark−Houwink equation, was 0.105. This small value was consistent with a highly branched compact structure.[13] Therefore, these results of the SEC, SLS, and solution viscosity measurements suggested that **2a** and **2b** were highly branched spherical molecules, i.e., hyperbranched carbohydrate polymers.

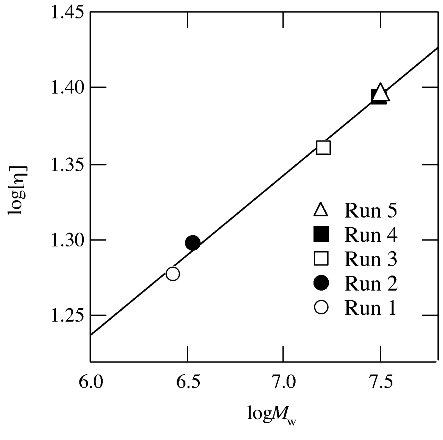
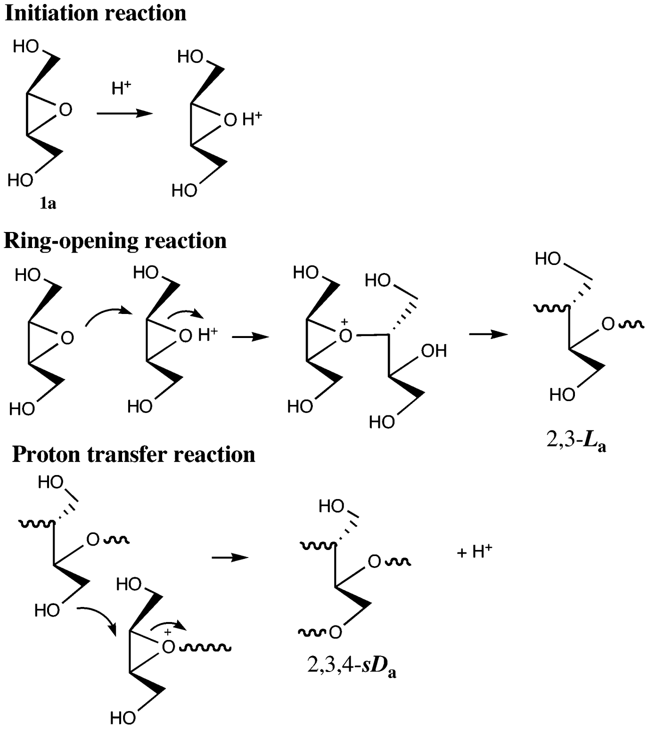


Figure 5. Logarithmic plots of $[\eta]-M_{w,SLS}$ for **2a**.

Polymerization Mechanism. Hyperbranched carbohydrate polymers **2a** and **2b** mainly consisted of DL-threitol and erythritol repeating units, respectively, as shown in Chart 2 and Chart 3, respectively. The polymerization, therefore, proceeded through a mechanism similar to the ring-opening multibranching polymerization of glycidol, which was reported by Kubisa and Penczek.[1,2] Scheme 3 represents the proposed mechanism for the polymerization of **1a**. In the polymerization system, the oxygen atom of the epoxy group of **1a** was protonated, and the protonated **1a** reacted with the oxygen atom of the epoxy group from another monomer, thus leading to 2,3-$\boldsymbol{L}_a$. The branched unit for **2a** should be produced by the proton-transfer reaction of the hydroxy groups in the polymer chain with the oxonium cation end of the other polymer chain. The polymerization of **1b** proceeded through a mechanism similar to that for **1a** to produce the hyperbranched carbohydrate polymer, **2b**.

Scheme 3. A Proposed Mechanism for Ring-Opening Multibranching Polymerization with Proton-Transfer Reaction



Conclusions

The polymerization of 2,3-anhydroerythritol (**1a**) and 2,3-anhydro-DL-threitol (**1b**) proceeded through the ring-opening reaction with a proton-transfer reaction mechanism, i.e., the ring-opening multibranching polymerization. The resulting polytetritols free from cyclic units were the hyperbranched carbohydrate polymers **2a** and **2b** essentially consisting of DL-threitol and erythritol units, respectively, which differed from the hyperbranched polytetritol prepared from 1,4-anhydroerythritol (**3a**) and 1,4-anhydro-L-threitol (**3b**). The weight-average molecular weight values ($M_{w,SLS}$s) were remarkably higher than those of the hyperbranched carbohydrate polymer prepared by the ring-opening multibranching polymerization of **3a** and **3b**. The three-dimensional properties characterized by size exclusion chromatography, static light scattering, and the viscosity measurements indicated that **2a** and **2b** should be spherical molecules.

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