Synthesis of Hyperbranched Carbohydrate Polymer by Ring-Opening Multibranching Polymerization of 1,4-Anhydroerythritol and 1,4-Anhydro-L-threitol

Tomoko Imai,[†] Toshifumi Satoh,[†,‡] Harumi Kaga,[§] Noriaki Kaneko,[||] and Toyoji Kakuchi*[,†]

Division of Molecular Chemistry, Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan, Division of Innovative Research, Creative Research Initiative "Sousei" (CRIS), Hokkaido University, Sapporo 060-0808, Japan, National Institute of Advanced Industrial Science and Technology (AIST), 2-17-2-1 Tsukisamu-Higashi, Toyohira-ku, Sapporo 062-8517, Japan, and COSMOTEC Company, 2-3-9 Hongo, Tokyo 113-0033, Japan

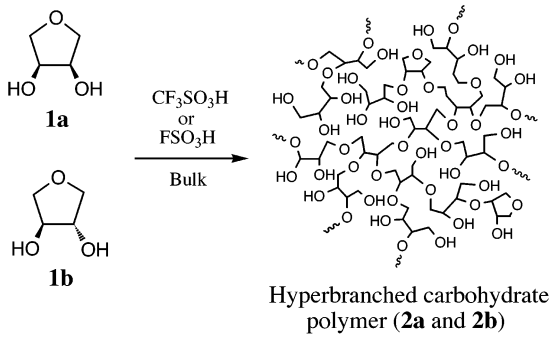
Received December 1, 2003; Revised Manuscript Received February 22, 2004

ABSTRACT: 1,4-Anhydroerythritol (**1a**) and 1,4-anhydro-L-threitol (**1b**) were polymerized using trifluoromethanesulfonic acid (CF_3SO_3H) or fluorosulfonic acid (FSO_3H) 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**) mainly consisting of erythritol and L-threitol units, respectively. The degrees of branching (DB) estimated by the ^{13}C NMR spectra of **2a** and **2b** were ca. 0.28−0.47. The weight-average molecular weight ($M_{w,SLS}$) values (3.2×10^4−5.1×10^5) estimated using static laser light scattering (SLS) of the resulting hyperbranched carbohydrate polymers were significantly higher than the weight-average molecular weight ($M_{w,SEC}$) values (1.5×10^3−1.4×10^4) estimated using size exclusion chromatography (SEC). The solution viscosities of **2a** and **2b** were very low, and the intrinsic viscosities ([η]) of **2a** and **2b** were in the range from 3.26×10^{-2} to 7.30×10^{-2} dL·g^{-1}. The three-dimensional properties characterized by the SLS and viscosity measurements indicated that **2a** and **2b** should be nanoscale particles.

Introduction

Hyperbranched polymer, of which the theoretical concept was previously established by Flory,[1] has recently attracted a great deal of attention as one of the dendritic macromolecules from the viewpoint of the synthetic advantage of a one-pot reaction. Thus, there are many synthetic methods for producing various kinds of hyperbranched polymers, such as (I) polycondensation of AB_x monomers, (II) self-condensing vinyl polymerization, and (III) ring-opening multibranching polymerization.[2,3] Ring-opening multibranching polymerization was first reported by Suzuki et al. in the polymerization of cyclic carbamate monomer using palladium catalyst.[4] Frey et al. reported that a hyperbranched aliphatic polyether was prepared by the ring-opening multibranching polymerization of glycidol using an anionic initiator.[2] In addition, Penczek et al.,[5] Hult et al.,[6] and Yan et al.[7,8] independently reported the synthesis of hyperbranched poly(hydroxy ether)s by the cationic polymerization of 3-ethyl-3-(hydroxymethyl)oxetane. Recently, we have proposed hyperbranched carbohydrate polymers as a novel macromolecular architecture, such as the hyperbranched 2,5-anhydro-D-glucitol[9] from the cationic cyclopolymerization of 1,2:5,6-dianhydro-D-mannitol and the hyperbranched D-mannose[10] from the cationic polymerization of 1,6-anhydro-D-mannopyranose.

Scheme 1

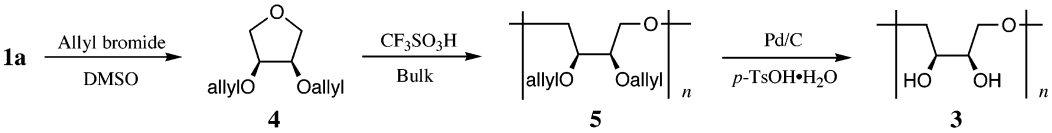


To utilize hyperbranched carbohydrate polymers as functional raw materials, it is important to expand the limit and scope of the ring-opening multibranching polymerization method in connection with the structure of the applicable monomer and the resulting polymers. Thus, there are various kinds of anhydro sugars, so that it is of great interest to elucidate characteristics of the ring-opening multibranching polymerization based on monomer structures along with resulting hyperbranched carbohydrate polymers. We now report the ring-opening multibranching polymerization of 1,4-anhydroerythritol (**1a**) and 1,4-anhydro-L-threitol (**1b**) using trifluoromethanesulfonic acid (CF_3SO_3H) or fluorosulfonic acid (FSO_3H), as shown in Scheme 1. The polymerization mechanism is discussed by determining the structure of the resulting polymers, such as the constitutional units and degree of branching. In addition, the hyperbranched poly(erythritol) (**2a**) is characterized on the basis of static laser light scattering and viscosity measurements, which are compared with a linear polymer of (1→4)-erythritol (**3**).

* To whom correspondence should be addressed. Telephone (fax): +81-11−706-6602. E-mail: kakuchi@poly-mc.eng.hokudai.ac.jp.
[†] Division of Molecular Chemistry, Hokkaido University.
[‡] CRIS, Hokkaido University.
[§] AIST.
[||] COSMOTEC.

10.1021/ma0358024 CCC: $27.50
Published on Web 04/09/2004

Scheme 2



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 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 distribution (M_w/M_n) of the polymer samples were calculated on the basis of poly(ethylene glycol) calibration. SEC of the organic solvent-soluble polymer was performed in chloroform at 40 °C using a JASCO GPC-900 system equipped with two polystyrene gel columns (Shodex KF-804L; 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 of the polymer samples were calculated on the basis of 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 UV-310 and JAI RI-5HC detectors and two JAI JAIGEL-3H polystyrene columns (pore size 10−20 nm, bead size 10−20 μm, exclusion limit 7×10^4). A static laser light scattering (SLS) measurement was performed in aqueous $NaNO_3$ solution (0.2 mol·L^{-1}) or toluene at 40 °C using an Otsuka Electronics CALLS 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. L-Threitol (Tokyo Kasei Co., >98%), erythritol (Tokyo Kasei Co., 99%), trifluoromethanesulfonic acid (CF_3SO_3H) (Aldrich, 98%), fluorosulfonic acid (FSO_3H) (Aldrich, triple distilled), dry tetrahydrofuran (THF) (Kanto Kagaku Co., stabilizer free, >99.5%), chloroform (Kanto Kagaku Co., 99%), toluene (Kanto Kagaku Co., >99.5%), allyl bromide (Kanto Kagaku Co., >99%), dimethyl sulfoxide (DMSO) (Junsei Chemical Co., 99%), *n*-hexane (Junsei Chemical Co.), magnesium sulfate anhydrous (Junsei Chemical Co., 99.5%), ethyl alcohol (Japan Alcohol Trading Co., 99%), and palladium/charcoal activated (Pd/C, 10% Pd) (Merck) were used without further purification. Sodium hydride (NaH) (Kanto Kagaku Co., dispersion in paraffin liquid, 60%) was used after washing with *n*-hexane. The dialysis membranes (Spectra Por R, MWCO 1000, and Spectra Por R, Cellulose ester MWCO 500) were purchased from Spectrum Laboratories, Inc. 1,4-Anhydroerythritol (**1a**)[11] and 1,4-anhydro-L-threitol (**1b**)[12] were synthesized from erythritol and L-threitol, respectively, according to the methods of Thiem et al.

Synthesis of 1,4-Anhydro-2,3-di-*O*-allylerythritol (4). NaH (1.59 g, 66.3 mmol) and allyl bromide (38 mL) in DMSO (11 mL) was added to a solution of **1a** (3.00 g, 28.8 mmol) in dry THF (53 mL) at 45 °C. The reaction mixture was stirred at 45 °C for 1 h and then at room temperature for 18 h. The mixture was poured into a large amount of water and extracted three times with chloroform. The combined extracts were evaporated under reduced pressure, and then the residue was purified by column chromatography on silica gel with hexane/ethyl acetate (3:1 v/v) to gives **4** as a colorless liquid (R_f = 0.32) in a 56.7% yield (3.01 g). ^{1}H NMR ($CDCl_3$) δ: 5.99−5.82 (m, allyl-CH═, 2H), 5.30 (ddd, $^3J_{trans}$ = 17.2 Hz, J_{gem} = 3.2 Hz, ^4J = 1.6 Hz, allyl trans ═CH_2, 2H), 5.20 (ddd, $^3J_{cis}$ = 10.4 Hz, J_{gem} = 2.7 Hz, ^4J = 1.4 Hz, allyl cis ═CH_2, 2H), 4.16−4.05 (m, allyl −CH_2−, 4H), 4.05−4.00 (m, CH, H2 and H3, 4H), 3.97−3.92 (m, CH_2, H1 and H4, 2H), 3.85−3.79 ppm (m, CH, H1 and H4, 2H). ^{13}C NMR ($CDCl_3$) δ: 134.68 (allyl, −CH═), 117.42 (allyl, ═CH_2), 77.49 (C2 and C3), 71.33 (allyl, −CH_2−), 70.38 ppm (C1 and C4). Anal. Calcd for $C_{10}H_{16}O_3$ (184.2): C, 63.51; H, 8.29. Found: C, 63.60; H, 8.56. FI-MS: *m*/*z* (relative intensity): 184 (M^+, 100), 185 (MH^+, 41.1).

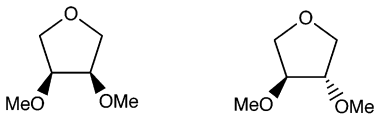
Synthesis of (1→4)-2,3-Diallylerythritol (5). All procedures were performed under a nitrogen atmosphere. Compound **4** (5.00 g, 27.2 mmol) was placed in an ampule and dried under reduced pressure for 18 h. After addition of trifluoromethanesulfonic acid (CF_3SO_3H, 0.270 g, 1.80 mmol), the ampule was sealed and cooled at −25 °C for 240 h. The polymerization mixture was quenched by adding water (5 mL) and then neutralized with aqueous sodium hydrogen carbonate solution. The mixture was extracted three times with chloroform, dried with magnesium sulfate anhydrous, filtered, and evaporated. The residue was purified using a dialysis membrane (MWCO 1000) in chloroform. After dialysis, the residue was dried in vacuo to give the polymer (original product) as a yellowish liquid in 45.8% yield (2.29 g). The $M_{w,SEC}$ and M_w/M_n were 4.65×10^4 and 3.97, respectively. ^{1}H NMR ($CDCl_3$) δ: 5.94−5.85 (m, allyl-CH═, 2H), 5.25 (d, $^3J_{trans}$ = 17.3 Hz, allyl, trans ═CH_2, 2H), 5.12 (d, $^3J_{cis}$ = 10.5 Hz, allyl, ═CH_2, 2H), 4.20−3.92 (m, allyl −CH_2−, 4H), 3.68−3.43 (m, CH and CH_2, 6H). ^{13}C NMR ($CDCl_3$) δ: 135.04 (allyl, −CH═), 116.73 (allyl, ═CH_2), 78.22, 78.13 (C2 and C3), 71.82, 71.77 (allyl, −CH_2−), 71.55, 71.43 ppm (C1 and C4).

The original product (2.29 g) was dissolved in chloroform (23 mL). Part of the solution (2.3 mL) was applied to the preparative SEC, and then the eluents with the retention times of 33−47 min were fractionalized. This procedure was repeated 10 times. The combined fractions were evaporated and then dried in a vacuum to give **5** (1.12 g) in a 22.4% yield. The $M_{w,SEC}$ and M_w/M_n were 1.50×10^4 and 1.98, respectively, and the $M_{w,SLS}$ was 1.29×10^4 (dn/dc = -8.86×10^{-2}).

Deallylation of 5. Ethyl alcohol (30 mL), water (10 mL), 10% Pd/C (2 g), and *p*-toluenesulfonic acid monohydride (500 mg, 2.63 mmol) were added to a solution of **5** (1.12 g, 6.08 unit mmol) in toluene (10 mL), and then the mixture was refluxed for 10 h. After the reaction mixture was cooled to room temperature, Pd/C was filtered off and the filtrate was purified using a dialysis membrane (MWCO 1000) in water. After dialysis, the residue was freeze-dried to give a white powder of (1→4)-erythritol (**3**) (0.425 g) in a 67.1% yield. The $M_{w,SEC}$ and M_w/M_n were 2000 and 1.72, respectively, and the $M_{w,SLS}$ was 3600 (dn/dc = 1.09×10^{-2}). ^{1}H NMR (D_2O) δ: 4.03−3.50 ppm (broad). ^{13}C NMR (D_2O) δ: 72.61 (C1 and C4), 71.08 (C2 and C3), 63.25 ppm (CH_2OH, terminal).

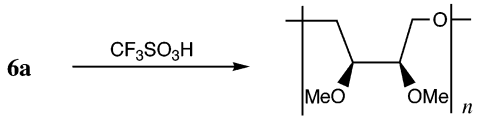
Synthesis of 1,4-Anhydro-2,3-di-*O*-methylerythritol (6a) and 1,4-Anhydro-2,3-di-*O*-methyl-L-threitol (6b). 1,4-Anhydro-2,3-di-*O*-methylerythritol (**6a**)[11] and 1,4-anhydro-2,3-di-*O*-methyl-L-threitol (**6b**)[12] were synthesized from erythritol and L-threitol, respectively, using a procedure similar to that reported by Thiem. **6a**: Yield, 76.1%. ^{1}H NMR ($CDCl_3$) δ: 3.97−3.90 (m, CH, H2 and H3, 2H and CH_2, H1 and H4, 2H), 3.87−3.80 (m, CH_2, H1 and H4, 2H), 3.45 ppm (s, methoxy, 6H). ^{13}C NMR ($CDCl_3$) δ: 79.68 (C2 and C3), 70.38 (C1 and C4), 57.95 ppm (methoxy). **6b**: Yield, 64.6%. ^{1}H NMR ($CDCl_3$) δ: 3.93 (dd, J_{gem}= 9.76 Hz, J_{vic}= 4.64 Hz, CH_2, H1 and H4, 2H), 3.87−3.80 (m, CH, H2 and H3, 2H), 3.78 (dd, J_{gem}= 9.75 Hz, J_{vic}= 1.78 Hz, CH_2, H1 and H4, 2H), 3.38 ppm (s, methoxy, 6H). ^{13}C NMR ($CDCl_3$) δ: 84.48 (C2 and C3), 71.31 (C1 and C4), 57.09 ppm (methoxy).

Chart 1



6a **6b**

Scheme 3



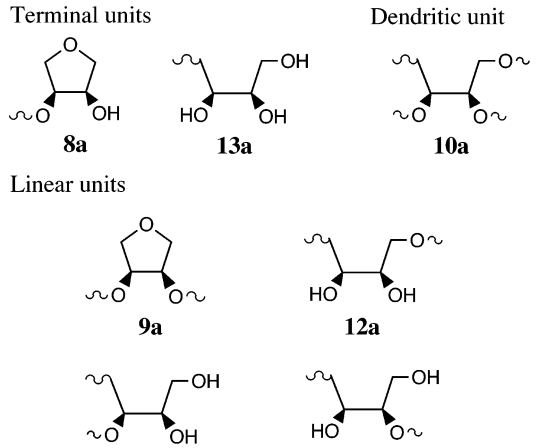
7

Synthesis of (1→4)-2,3-Di-*O*-methylerythritol (7). A procedure similar to that used for the synthesis of polymer **5** was applied to the polymerization of **6a** (1.00 g, 7.57 mmol) at −20 °C for 240 h. Polymer **7** was obtained as a colorless liquid in a 31.8% yield (0.318 g). The $M_{w,SEC}$ and M_w/M_n were 2.26 × 10^4 and 1.86, respectively, and the $M_{w,SLS}$ was 4.10 × 10^4 (dn/dc = −8.97 × 10^{-2}). ^{1}H NMR ($CDCl_3$) δ: 3.56−3.35 (m, CH_2 H1 and H4, 4H), 3.33−3.20 ppm (m, CH, H2, H3, 2H and methoxy, 6H). ^{13}C NMR ($CDCl_3$) δ: 79.70 (C2 and C3), 70.41 (C1 and C4), 58.15 ppm (methoxy).

Typical Procedure for Polymerization of 1,4-Anhydroerythritol (1a). All procedures were performed under a nitrogen atmosphere. Compound **1a** (500 mg, 4.80 mmol) was placed in an ampule and dried under reduced pressure for 18 h. After addition of CF_3SO_3H (36.0 mg, 0.240 mmol), the ampule was sealed and heated at 60 °C for 240 h. The polymerization mixture was quenched by adding water (5 mL), then neutralized with aqueous sodium hydrogen carbonate solution, and evaporated. The residue was dissolved in water (1 mL) and then poured into a large amount of tetrahydrofuran. The precipitated polymer was filtered off, and the filtrate was purified using a dialysis membrane (MWCO 1000) in the water. After dialysis, the residue was freeze-dried to give a white powdery polymer of **2a** in a 46.4% yield (232 mg). The $M_{w,SEC}$ and M_w/M_n were 2270 and 1.80, respectively, and the $M_{w,SLS}$ was 5.90 × 10^4 (dn/dc = 1.44 × 10^{-1}). ^{1}H NMR (D_2O) δ: 4.42−4.36 (m, H3 for 2-bonded 1,4-anhydroerythritol (**8a**) as the terminal unit, 1H), 4.24−4.19 (m, H2 and H3 for 2,3-bonded 1,4-anhydroerythritol (**9a**) as the linear unit, 2H), 4.17−4.09 (m, H2 for **8a**, 1H), 4.07−4.03 (m), 4.03−3.87 (m), 3.87−3.34 ppm (broad). ^{13}C NMR (D_2O) δ: 81.68 (C2 and C3 for 1,2,3,4-multibonded erythritol (**10a**) as the dendritic unit, and C1 for 1,2,3-bonded erythritol (**11a**) as the semidendritic unit), 80.13−80.03 (C3 for **8a**), 79.74−78.71 (C2 and C3 for **9a**), 75.72 (CH), 75.54 (CH), 75.26 (CH), 74.87 (CH), 74.00−73.52 (CH), 72.90 (CH_2), 72.75 (C1 and C4 for 1,4-bonded erythritol (**12a**) as the linear unit, and C1 for 1-bonded erythritol (**13a**) as the terminal unit), 72.45 (CH_2), 72.34 (CH_2), 72.06 (CH_2), 71.98 (CH), 71.77 (C1 and C4 for **10a**, and C1 for **11a**), 71.45 (CH), 71.13 (C2 and C3 for **12a**, and C2 for **11a**), 70.56−70.48 (CH, **8a**, C2), 70.36 (CH), 70.11 (CH), 69.87 (CH), 69.60 (C4 for **8a**), 68.80−68.65 (C1 for **8a**, C1 and C4 for **9a**), 68.16 (CH), 64.43 (CH_2OH), 63.30 (C4 for **13a**), 63.08 (CH_2OH), 62.90 (CH_2OH), 60.77 (CH_2OH), 60.28 ppm (C4 for **11a**).

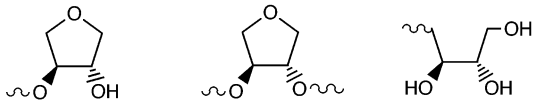
Procedure for Polymerization of 1,4-Anhydro-L-threitol (1b). A procedure similar to that used for **1a** was applied to **1b** (500 mg, 4.8 mmol) at 80 °C for 120 h. A white powdery polymer of **2b** was obtained in a 41.0% yield (205 mg). The $M_{w,SEC}$ and M_w/M_n were 7340 and 4.32, respectively, and the $M_{w,SLS}$ was 2.26 × 10^5 (dn/dc = 1.33 × 10^{-1}). ^{1}H NMR (D_2O) δ: 4.46−4.35 (m, H3 for 2-bonded 1,4-anhydro-L-threitol (**8b**) as the terminal unit, 1H), 4.21−4.14 (m, H2 and H3 for 2,3-bonded 1,4-anhydro-L-threitol (**9b**) as the linear unit, 2H), 4.14−4.04 (m), 4.01 (m, H2 for **8b**, 1H), 3.98−3.45 ppm (m). ^{13}C NMR (D_2O) δ: 85.60−85.52 (C3 for **8b**), 83.15 (C2 and C3 for **9b**), 81.56 (CH), 80.21−78.59 (CH), 77.17 (CH), 74.34 (C2 for **8b**), 73.60 (C1 for **8b** and **9b**), 72.67 (CH_2), 72.32 (CH_2), 71.68 (CH_2), 71.51 (C4 for **8b** and **9b**), 71.34−70.87 (CH), 70.86 (CH_2), 70.77−70.00 (CH), 69.43 (CH), 68.95 (CH_2), 67.91 (CH), 64.39 (CH_2OH), 64.03 (CH_2OH), 63.15 (C4 for 1-bonded L-threitol (**13b**) as the terminal unit), 62.91 (CH_2OH), 60.98 (CH_2OH), 60.17 ppm (CH_2OH).

Chart 2



8a **13a** **10a** **9a** **12a** **11a**

Chart 3



8b **9b** **13b**

Ratio of 1,4-Anhydrotetritol Unit in the Polymer. The ratios of the 1,4-anhydroerythritol units (**8a** and **9a**) in **2a** and the 1,4-anhydro-L-threitol units (**8b** and **9b**) in **2b** were estimated from the ^{1}H NMR spectra of **2a** and **2b**, respectively. In the ^{1}H NMR spectrum of **2a** (Figure 2), the signals at 4.42−4.36 and 4.24−4.19 ppm were the 3-methine protons due to **8a** and the 2,3-methine protons due to **9a**, respectively. The ratio of 1,4-anhydroerythritol units in **2a** was estimated as

[integrated area of (6(3-methine proton due to **8a**) + 3(2,3-methine protons due to **9a**))]/ [integrated area of total proton peak at 4.42−3.34 ppm]

A estimation similar to that used for **2a** was applied to **2b**. In the ^{1}H NMR spectrum of polymer **2b** (Figure 3a), the signals at 4.46−4.35 and 4.21−4.14 ppm were assigned to 3-methine protons due to **8b** as the terminal unit and 2,3-methine protons due to **9b** as the linear unit, respectively.

Degree of Branching. The degrees of branching (DBs) of **2a** and **2b** prepared from the AB_3 monomer were determined by Frey's equation[13] from the ratio of the terminal units. In the ^{13}C NMR spectrum of **2a**, the signal at 63.30 ppm was assigned to the C4 methylene carbon due to **13a**. The ratio of **13a** [$T_{13a}/(D + sD + L + T)$] was estimated from the integrated area of the methylene carbon peaks, as

$$\frac{2(\text{integrated area of C4 methylene peak for } \mathbf{13a})}{\text{integrated area of total methylene peak}}$$

The ratio of **8a** [$T_{8a}/(D + sD + L + T)$] was estimated from the ^{1}H NMR spectrum of **2a**, as

$$\frac{6(\text{integrated area of 3-methine proton due to } \mathbf{8a})}{\text{integrated area of total proton peak at 4.42−3.34 ppm}}$$

Table 1. Bulk Polymerization of 1,4-Anhydroerythritol (1a) and 1,4-Anhydro-L-threitol (1b) Using Trifluoromethanesulfonic Acid (CF_3SO_3H) or Fluorosulfonic Acid (FSO_3H)

run no.	monomer	catalyst	temp/°C	[M]/[cat.]	time/h	yield[a]/%	$M_{w,SEC}$ (M_w/M_n)[b]	$M_{w,SLS} \times 10^{-4}$ [c]	$[\eta] \times 10^{-2}$ [d]
1	**1a**	CF_3SO_3H	23	20	240	trace			
2	**1a**	CF_3SO_3H	60	20	120	45.9	3650 (2.57)	7.1	4.27
3	**1a**	CF_3SO_3H	60	10	240	43.7	1520 (1.62)	3.2	3.26
4	**1a**	CF_3SO_3H	60	20	240	46.4	2270 (1.80)	5.9	3.64
5	**1a**	CF_3SO_3H	60	40	240	37.4	3440 (1.62)	11.9	3.91
6	**1a**	CF_3SO_3H	80	20	120	43.5	14400 (7.86)	51.0	7.30
7	**1a**	FSO_3H	60	10	240	47.7	1530 (2.57)	1.0	3.73
8	**1b**	CF_3SO_3H	80	20	120	41.0	7340 (4.32)	22.6	4.59

[a] THF-insoluble parts. [b] Determined by size exclusion chromatography in 0.2 mol·L^{-1} aqueous $NaNO_3$ solution using PEG as standard. [c] Determined by static light scattering in 0.2 mol·L^{-1} aqueous $NaNO_3$ solution. [d] Obtained from Canon-Fenske viscometer in $NaNO_3$ aqueous solution.

Thus, the total terminal units ratio of polymer **2a** [$T/(D + sD + L + T)$] was estimated as

$$\frac{T_{13a}}{D + sD + L + T} + \frac{T_{8a}}{D + sD + L + T}$$

The DB of polymer **2a** was calculated as shown in eq 1.

$$\mathrm{DB} = \frac{3}{2}\left(\frac{T}{D + sD + L + T}\right) = \frac{3}{2}\left(\frac{T_{13a}}{D + sD + L + T} + \frac{T_{8a}}{D + sD + L + T}\right) \quad (1)$$

This calculation method was applied to **2b**. In the ^{13}C NMR spectrum of **2b**, the signal at 63.15 ppm was due to the C4 methylene carbon for **13b**. In the ^1H NMR spectrum of **2b**, the signal at 4.46−4.35 ppm was due to the C3 methine proton of **8b**. From the ratio of **13b** and **8b**, the total terminal units ratio and DB of **2b** were estimated.

Results and Discussion

Polymerization. The bulk polymerizations of 1,4-anhydroerythritol (**1a**) and 1,4-anhydro-L-threitol (**1b**) were carried out using trifluoromethanesulfonic acid (CF_3SO_3H) or fluorosulfonic acid (FSO_3H) at 23−80 °C. After the initiator was added to the monomer, the polymerization proceeded homogeneously and the viscosity of the polymerization systems immediately increased with the polymerization progress. The resulting product was a white powdery polymer, which was soluble in water, sparingly soluble in methanol, and insoluble in other organic solvents. Table 1 lists the polymerization results. For the polymerization of **1a** using CF_3SO_3H in the [**1a**]/[CF_3SO_3H] molar ratio of 20, the yield of polymer (**2a**) was ca. 45% at 60 and 80 °C, while it was a trace at 23 °C. The [**1a**]/[CF_3SO_3H] molar ratio affected the weight-average molecular weight ($M_{w,SLS}$) values measured by the static laser light scattering (SLS) of the resulting polymer. For the polymerization at 60 °C for 240 h, the $M_{w,SLS}$'s were in the range from 3.2×10^4 to 11.9×10^4, which increased with increasing the [**1a**]/[CF_3SO_3H] molar ratio from 10 to 40. The polymerization temperature also affected the $M_{w,SLS}$; i.e., for the [**1a**]/[CF_3SO_3H] molar ratio of 20 for 120 h, the $M_{w,SLS}$'s were 7.1×10^4 and 5.1×10^5 at 60 and 80 °C, respectively. The extension of the polymerization time led to a decrease in $M_{w,SLS}$ as a comparison between runs 2 and 4. A similar result was reported in the ring-opening polymerization of 1,4-anhydro-2,3-di-*O*-methylerythritol (**6a**) and 1,4-anhydro-2,3-di-*O*-ethylerythritol using CF_3SO_3H and FSO_3H.[11,12] In the polymerization of **1a** using FSO_3H as a catalyst, the $M_{w,SLS}$ was low as 1.0×10^4, which should be related to the lower acidity of FSO_3H ($pK_a = -12.60$) in contrast to CF_3SO_3H ($pK_a = -19.12$).[12] The $M_{w,SLS}$ values of the polymer (**2b**) prepared from **1b** were lower than those of **2a**; i.e., for the [**1**]/[CF_3SO_3H] molar ratio of 20 at 80 °C for 240 h, the $M_{w,SLS}$ value of **2b** was 22.6×10^4, while that of **2a** was 51.0×10^4. The lower $M_{w,SLS}$ value of **2b** compared to that of **2a** should be caused by the difference in the ring strain effect between **1a** and **1b**; i.e., the ring-opening reaction of the tetrahydrofuranyl ring in **1a** proceeded more easily than that of **1b**. In fact, Thiem et al. reported that the polymerization of the 2,3-dimethyl substituted **1b** of 1,4-anhydro-2,3-di-*O*-methyl-L-threitol (**6b**) produced only a dimer in less than 1% yield due to the ring strain effect, though 2,3-dimethyl substituted **1a** of **6a** was polymerized to afford a polymeric product.[12]

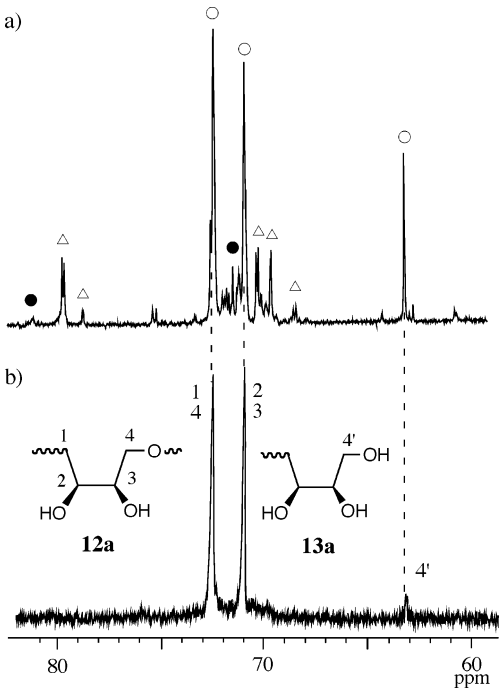


Figure 1. ^{13}C NMR spectra of a) polymer **2a** (run 2) and (b) linear polymer **3**.

Polymer Structure. To investigate the polymer structure, the ^{13}C NMR spectrum of the polymer was compared with that of a linear carbohydrate polymer of (1→4)-erythritol (**3**) as shown in Figure 1. For the ^{13}C NMR spectrum of **3**, the major signals at 72.61 and 71.08 ppm were assigned to the C1,4 and C2,3 carbons for 1,4-bonded erythritol (**12a**) as the linear unit, respectively. The small signal at 63.25 ppm was assigned to the C4 carbon for 1-bonded erythritol (**13a**) as the terminal unit. On the other hand, the spectrum

Table 2. Structural Units Ratio and Degree of Branching (DB) in Polymers 2a and 2b

run no.	polymer	tetritol unit (tetritol terminal unit (**13a**))[a]/%	1,4-anhydrotetritol unit (1,4-anhydrotetritol terminal unit (**8a**))[b]/%	total terminal unit (**8a** + **13a**)[c]/%	DB
1	**2a**	nd[d]	nd[d]	nd[d]	nd[d]
2	**2a**	93.2 (19.2)	6.8 (5.2)	24.5	0.37
3	**2a**	92.3 (22.5)	7.7 (7.3)	29.8	0.45
4	**2a**	89.6 (22.8)	10.4 (7.8)	30.6	0.46
5	**2a**	85.3 (23.1)	14.7 (8.5)	31.6	0.47
6	**2a**	91.3 (14.6)	8.7 (7.1)	21.7	0.33
7	**2a**	92.9 (12.7)	7.1 (5.8)	18.5	0.28
8	**2b**	67.2 (5.1)[e]	32.8 (19.8)[f]	24.9[g]	0.37

[a] Determined by ^{13}C NMR spectra. [b] Determined by ^{1}H NMR spectra. 1,4-Anhydrotetritol unit = **8a** + **9a**. [c] Estimated from total terminal units (Experimental Section). [d] Not determined. [e] Tetritol terminal unit of **13b**. [f] 1,4-anhydrotetritol unit = **8b** + **9b**. [g] Total terminal unit = **8b** + **13b**.

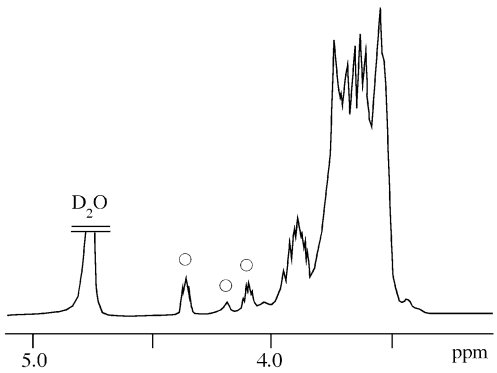


Figure 2. ^{1}H NMR spectrum of polymer **2a** (run 2).

of **2a** consisted of a number of split and broad signals. The signals marked with open circles at 72.75, 71.13, and 63.30 ppm were very close to the chemical shifts of **3**, indicating that **2a** contained **12a** and **13a**. In the comparison with the chemical shifts of (1→4)-2,3-di-*O*-methylerythritol (**7**) as the model compound, the signals marked with closed circles at 81.68 and 71.77 should be assigned to 1,2,3,4-multibonded erythritol (**10a**) as the dendritic unit. These results indicated that **2a** should be a branched polymer having numerous erythritol terminal units, i.e., a hyperbranched carbohydrate polymer. In addition, the ^{13}C NMR spectrum of **2a** exhibited the presence of the tetrahydrofuranosyl units of 2,3-bonded 1,4-anhydroerythritol (**9a**) as the linear unit and 2-bonded 1,4-anhydroerythritol (**8a**) as the terminal unit; i.e., in the comparison with the chemical shifts of **1a** and **6a** as the model compounds, the signals marked with open triangles at 80.13−80.03, 79.74−78.71, 70.56−70.48, 69.60, and 68.80−68.65 ppm were assigned to the carbons for **8a** and **9a** (Experimental Section and Supporting Information).

In the ^{1}H NMR spectrum of **2a** (Figure 2), the signal was broad and the signals marked by the open circles at 4.42−4.36, 4.17−4.09 and 4.24−4.19 ppm were assigned to the methine protons of **8a** and **9a** (Experimental Section and Supporting Information). From the ^{1}H NMR spectrum, the ratio of the 1,4-anhydroerythritol unit in **2a** was estimated as 6.8−14.7%, as listed in Table 2 (Experimental Section).

Figure 3 shows the ^{1}H NMR and ^{13}C NMR spectra of **2b**. The assignment of the signals was carried out by the comparison of 1,4-anhydro-L-threitol (**1b**), 2,3-di-*O*-methyl-1,4-anhydro-L-threitol (**6b**), and L-threitol as the model compounds. In the ^{1}H NMR spectrum of **2b**, the signals marked by the open circles at 4.46−4.35, 4.21−4.14, and 4.01 ppm were assigned to the methine protons for 2,3-bonded 1,4-anhydro-L-threitol (**8b**) as the

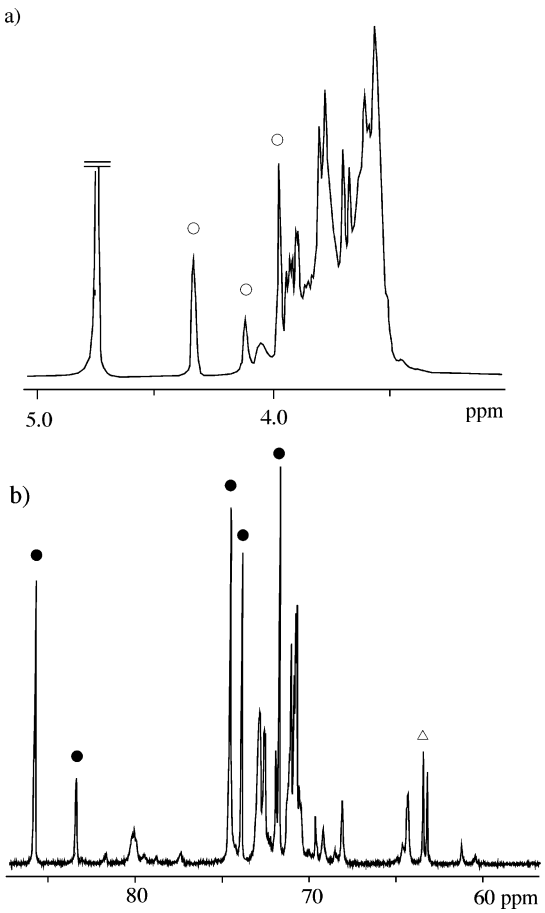
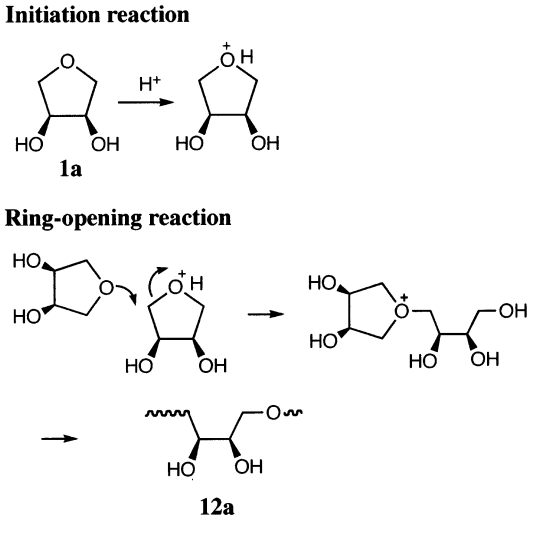


Figure 3. (a) ^{1}H NMR and (b) ^{13}C NMR spectra of polymer **2b**.

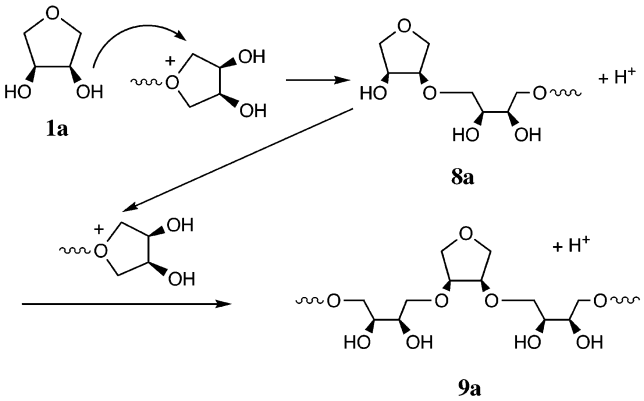
terminal unit and 2-bonded 1,4-anhydro-L-threitol (**9b**) as the linear unit. In the ^{13}C NMR spectrum of **2b**, the signals marked by the closed circles at 85.60−85.52, 83.15, 74.34, 73.60, and 71.51 ppm were also assigned to the carbons for **8b** and **9b**. The signal marked by the open triangle at 63.15 ppm was assigned to the 1-bonded L-threitol (**13b**) as the terminal unit (Supporting Information). Therefore, polymer **2b** consisted of 67.2% of the L-threitol unit and 32.8% of the 1,4-anhydro-L-threitol unit.

Degree of Branching. Monomers **1a** and **1b** are tetrahydrofurans having two hydroxy groups in a molecule; therefore they are classified as latent AB_3 type monomers. The degrees of branching (DBs) of **2a** and **2b** prepared from the AB_3 monomers are determined from the ratio of the terminal unit using Frey's equation.[13] **2a** contained two types of terminal unit, i.e., **8a**

Scheme 4. Proposed Mechanism for Ring-Opening Multibranching Polymerization



Scheme 5. Proposed Mechanism for Remaining Ring Unit in Polymer



and **13a**. The ratio of **13a** in **2a**, which was estimated from the ^{13}C NMR measurement, was varied from 12.7 to 23.1%, and that of **8a** in **2a** was from 5.2 to 8.5%. Therefore, the total ratio of the terminal units in **2a** was calculated as the values in the range of 18.5−31.6%, so that the DB of **2a** was determined as 0.28−0.47 from eq 1, as summarized in Table 2. For polymer **2b** containing **8b** and **13b**, a similar estimation used for polymer **2a** was applied. The ratios of **8b** and **13b** were 19.8 and 5.1%, respectively, and the DB was determined to be 0.37.

Polymerization Mechanism. Hyperbranched carbohydrate polymer **2a** mainly consisted of erythritol repeating units. Scheme 4 represents the proposed mechanism for the polymerization of **1a**. In the polymerization system, the 1,4-ether oxygen atom of **1a** was protonated and the protonated **1a** was reacted with the 1,4-ether oxygen atom of another monomer, thus leading to **12a**. The branched unit for **2a** should be produced by the proton-transfer reaction of the hydroxy groups in the erythritol unit with the oxonium cation of the protonated **1a**. The 1,4-anhydroerythritol units **8a** and **9a** should be formed by the proton-transfer reaction of the hydroxy groups in **1a** with an oxonium cation in the polymer without the ring-opening reaction, as shown in Scheme 5. Although the polymerization of **1b** proceeds through a mechanism similar to that for **1a**, the ring-opening reaction of **1b** should proceed more slowly than that of **1a** because of the ring strain effect.[12]

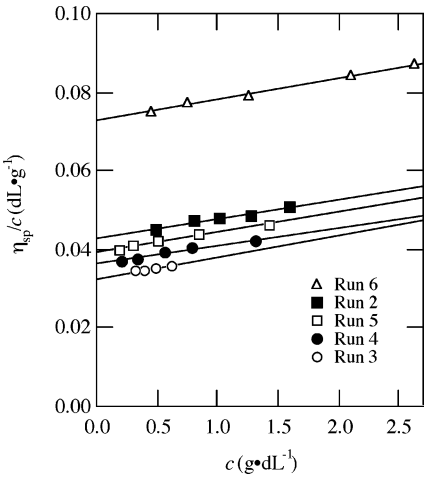


Figure 4. Viscosity versus concentration plots for polymer **2a**.

Three-Dimensional Property. For **2a**, the $M_{w,SLS}$ values (1.0×10^4−5.1×10^5) were ca. 6.5−35 times greater than the $M_{w,SEC}$ values (1.5×10^3−1.4×10^4). In contrast, for the linear polymer of **3**, the $M_{w,SLS}$ value of 3.6×10^3 was somewhat greater than the $M_{w,SEC}$ value of 2.0×10^3. The difference between the $M_{w,SLS}$ and the $M_{w,SEC}$ values for **2a** was significantly greater than that for **3**, indicating that the hyperbranched polymer of **2a** had a more spherical form in solution in comparison to the linear polymer of **3**.[3]

In addition, the three-dimensional property was characterized based on the viscosity study. Figure 4 shows the relation between the viscosity and concentration of **2a**. A linear dependence between the reduced viscosity and the concentration was observed, indicating that no aggregation of **2a** occurred in the polymer concentration represented in Figure 4. The intrinsic viscosities ([η]) are listed in Table 1. The solution viscosity of **2a** was low although **2a** had a high molecular weight; i.e., the [η] value was in the range 3.26×10^{-2}−7.30×10^{-2} dL•g^{-1} for the $M_{w,SLS}$ value of 1.0×10^4−5.1×10^5. On the other hand, the [η] value for the linear polymer of **3** was 3.27×10^{-2} dL•g^{-1} for $M_{w,SLS}$ of 3.6×10^3. For **2b**, the $M_{w,SLS}$ value of 2.26×10^5 was 30.8 times greater than the $M_{w,SEC}$ value of 7.3×10^3. A linear dependence between the reduced viscosity and the concentration was observed, indicating that no aggregation of **2b** also occurred and the [η] value was low as 4.59×10^{-2} dL•g^{-1}. Therefore, these results of the SEC, SLS, and viscosity measurements suggested that polymers **2a** and **2b** were highly branched spherical macromolecules, i.e., hyperbranched carbohydrate polymers.

Conclusions

The polymerization of 1,4-anhydroerythritol (**1a**) and 1,4-anhydro-L-threitol (**1b**) using trifluoromethanesulfonic acid (CF_3SO_3H) or fluorosulfonic acid (FSO_3H)

proceeded through the proton-transfer reaction mechanism to produce the hyperbranched carbohydrate polymer (**2a** and **2b**) mainly consisting of the erythritol or L-threitol units. The three-dimensional properties characterized by the static laser light scattering and the viscosity measurements indicated that **2a** and **2b** should be nanoscale particles. This was the first report of the synthesis of the hyperbranched polymer via the multibranching ring-opening polymerization of the tetrahydrofuranosyl alcohol as the novel type of monomer.

Acknowledgment. The authors thank the Akiyama Foundation (Japan), Hayashi Memorial Foundation for Female Natural Scientists, and Northern Advancement Center for Science and Technology (NOASTEC, Japan) for their financial support.

Supporting Information Available: ^{13}C NMR spectra for **8a,b**, **9a,b**, and **13a,b**. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Flory, P. J. *J. Am. Chem. Soc.* **1952**, *74*, 2718−2732.
(2) Sunder, A.; Hanselmann, R.; Frey, H.; Mülhaupt, R. *Macromolecules* **1999**, *32*, 4240−4246.
(3) Jikei, M.; Kakimoto, M. *Prog. Polym. Sci.* **2001**, *26*, 1233−1285.
(4) Suzuki, M.; Ii, A.; Saegusa, T. *Macromolecules* **1992**, *25*, 7071−7072.
(5) Bednarek, M.; Biedron, T.; Helinski, J.; Kaluzynski, K.; Kubisa, P.; Penczek, S. *Macromol. Rapid Commun.* **1999**, *20*, 369−372.
(6) Magnusson, H.; Malmström, E.; Hult, A. *Macromol. Rapid Commun.* **1999**, *20*, 453−457.
(7) Yan, D.; Hou, J.; Zhu, X.; Kosman, J. J.; Wu, H. S. *Macromol. Rapid Commun.* **2000**, *21*, 557−561.
(8) Mai, Y.; Zhou, Y.; Yan, D.; Lu, H. *Macromolecules* **2003**, *36*, 9667−9669.
(9) Imai, T.; Satoh, T.; Kaga, H.; Kaneko, N.; Kakuchi, T. *Macromolecules* **2003**, *36*, 6359−6363.
(10) Satoh, T.; Imai, T.; Ishihara, H., Maeda, T.;, Kitajyo, Y.; Narumi, A.; Kaga, H.; Kaneko, N.; Kakuchi, T. *Macromolecules* **2003**, *36*, 6364−6370.
(11) Thiem, J.; Häring, T. *Makromol. Chem.* **1987**, *188*, 711−718.
(12) Thiem, J.; Stieholt, W. A.; Häring, T. *Makromol. Chem.* **1989**, *190*, 1737−1753.
(13) Holter, D.; Frey, H. *Acta Polym.* **1997**, *48*, 30−35.

MA0358024