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ARTICLE

Ring-Opening Polymerization of a Benzylated 1,6-Anhydro-β-D-talopyranose and Synthesis of a New Polysaccharide, (1→6)-α-D-Talopyranan

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ABSTRACT: 1,6-Anhydro-2,3,4-tri-*O*-benzyl-β-D-talopyranose (**1**) was synthesized and polymerized to compare its polymerizability with that of other benzylated 1,6-anhydrohexopyranoses reported previously. In methylene chloride at −60 °C, phosphorus pentafluoride as the initiator gave stereoregular polymers (**2**) with number-average molecular weights (M_n) of 9500−19 600. The polymerizability was analyzed based on the configuration of the hydroxyl groups and conformational change of the pyranose ring during polymerization. The monomer reactivity ratios resulting from copolymerization with 1,6-anhydro-2,3,4-tri-*O*-benzyl-β-D-glucopyranose (**4**) were also compared. The present monomer **1** required a large amount of the initiator for polymerization. ^{31}P NMR results of polymerization suggested that considerable amounts of the initiator coordinated with not only the oxygen of the 1,6-anhydro ring of the monomer but also those of the polymer. This additional coordination of the initiator with the polymer oxygens is expected to decrease the initiation efficiency. Debenzylation resulted in a new stereoregular polysaccharide, (1→6)-α-D-talopyranan (**3**).

Introduction

Schuerch and Ruckel[1] reported the first chemical synthesis of a stereoregular polysaccharide by ring-opening polymerization of a 1,6-anhydro sugar derivative. In this method, the hydroxyl groups are protected with benzyl groups, which are subsequently removed to give the resulting polysaccharide. Numerous anhydro sugar derivatives have been synthesized, polymerized, and converted into natural or non-natural types of polysaccharides using this method.[2−5] These studies have shown that the benzyl group is the most suitable for protecting a hydroxyl group in ring-opening polymerization of anhydro sugars due to the convenience of its introduction and removal and its stability, without affecting polymerization. Among eight possible diastereomers of 1,6-anhydro-D-hexopyranoses shown in Figure 1, the glucose (Glc),[1,6−12] mannose (Man),[10,13] galactose (Gal),[9,10,14] allose (All),[15] and altrose (Alt)[16] tribenzylates have been polymerized to give the corresponding stereoregular (1→6)-α-D-hexopyranans that have high molecular weights except for the Alt monomer. The Alt benzylate had negligible homopolymerizability but could be copolymerized with the Glc benzylate. The polymerizability of the tribenzylated 1,6-anhydrohexopyranoses is in the order Man > Glc > Gal > All > Alt.[2] Although there are several factors that affect the polymerizability, the configuration of the hydroxyl groups of the anhydro sugars has the greatest influence.

Talose (Tal) is one of the three remaining aldohexoses whose ring-opening polymerization of its anhydro form has not yet been elucidated. D-Tal is a component of destomycin A,[17] hygromycin B,[18] and their related antibiotics[19] and is not found in a polysaccharide form in nature. The configurations of the hydroxyl groups are equatorial at the C2 and C4 positions and axial at the C3 position when the 1,6-anhydro ring is formed. Kobayashi and Schuerch[20] studied the relationship between the configuration of the hydroxyl groups of some 1,6-anhydro sugars and their potential energies for ring-opening polymerization. They proposed that the polymerizability is enhanced with an increase in the number of axial hydroxyl groups in the monomer, owing to the enhancement of the enthalpy originating from the conformational change of the pyranose ring from $^1C_4$ in the monomer to $^4C_1$ in the polymer. This proposition was verified by polymerizations of many derivatives of the five 1,6-anhydro sugars[2] mentioned above. However, the actual order of the polymerizability changes by several factors (e.g., the Man monomer is more reactive than the Glc monomer). Moreover, in the case of 1,6-anhydro sugars with the same number of axial hydroxyl groups, the major factor affecting the polymerizability has not yet been determined and thus requires further investigation.

Here we describe the synthesis and ring-opening polymerization of 1,6-anhydro-2,3,4-tri-*O*-benzyl-β-D-talopyranose (**1**), the sixth tribenzylated 1,6-anhydro-hexopyranose monomer. The polymerizability is analyzed by comparing the conversion and molecular weight of the resulting polymers with those of polymers obtained by ring-opening polymerization of other tribenzylated 1,6-anhydrohexopyranoses. In addition, copolymerization of **1** with 1,6-anhydro-2,3,4-tri-*O*-benzyl-β-D-glucopyranose (**4**), whose polymerizability is well-established, was attempted to derive the monomer reactivity ratios. Explanations of the polymerization potential of **1** will be developed mainly from the configuration of the hydroxyl groups and the conformational change of the pyranose ring during polymerization.

Experimental Section

Materials. All chemicals were reagent grade and used without further purification unless otherwise noted. Sodium hydride (Kishida Chemical Co., Ltd., Japan) was washed with hexane to remove the coating of mineral oil. Dichloromethane (99.8%, anhydrous; Sigma-Aldrich, Inc., Japan) and 1,2-dimethoxyethane (98%; Kishida Chemical Co., Ltd., Japan) were dried

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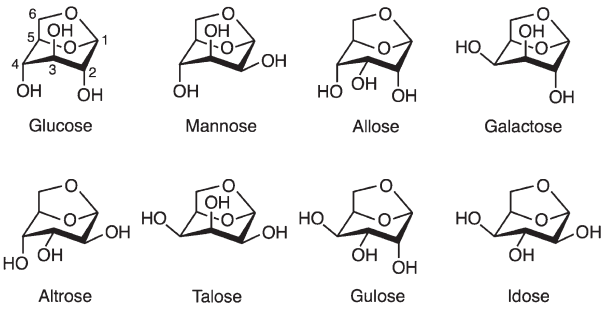


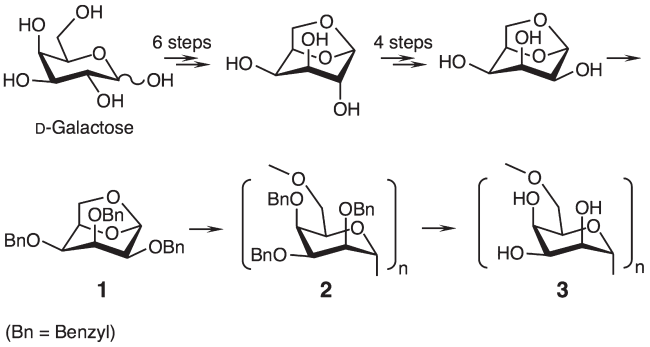
Figure 1. Eight possible 1,6-anhydro-β-D-hexopyranoses. The numeral denotes the position number of each carbon.

over CaH_2, and distilled just before use. *p*-Chlorobenzenediazonium hexafluorophosphate (Tokyo Chemical Industry Co., Ltd., Japan) was purified by recrystallization from water twice and dried under high vacuum. Another monomer **4** for copolymerization was prepared from 1,6-anhydro-2,3,4-tri-*O*-acetyl-β-D-glucopyranose[21] according to the literature[22] with some minor modifications. The identification and purity were confirmed by ^{1}H NMR and melting point measurements.

Measurements. ^{1}H and ^{13}C NMR spectra were recorded on a JEOL JNM-ECX400 spectrometer at 400 and 100 MHz, respectively, in $CDCl_3$ with tetramethylsilane or in D_2O with sodium 3-(trimethylsilyl)-1-propanesulfonate as internal reference. Quantitative ^{13}C NMR spectra were measured by an inverse gated decoupling method with a 45° pulse angle and delay time of 10 s. ^{31}P NMR spectra were obtained with a JEOL JNM-α500 spectrometer at 200 MHz in CD_2Cl_2 using phosphoric acid as external reference. DQF-COSY, HSQC, and HMBC measurements were carried out at 400 MHz with pulsed field gradients. The evolution time for the HMBC experiments was set to 60 ms. Melting points were measured by a Yamato MP-21 apparatus. Optical rotations were determined with a JASCO P-1020 polarimeter in a jacketed 1 dm cell. Preparative high-performance liquid chromatography (HPLC) was used for purification of **1** through a Wakosil 5SIL (10 mm × 300 mm) silica gel column (Wako Pure Chemical Industries, Ltd., Japan). Molecular weights and distribution of polymers were evaluated by means of gel permeation chromatography (GPC) based on standard polystyrenes (Shodex SM-105; Showa Denko Co., Ltd., Japan) in $CHCl_3$ or on standard pullulans (Shodex P-82; Showa Denko Co., Ltd., Japan) in 66.7 mM of phosphate buffer (pH 6.86). The columns were Tosoh TSKgel G3000H_{XL}, G4000H_{XL}, and G5000H_{XL} for organic phase and TSKgel G2500PW_{XL}, G3000PW_{XL}, and G4000PW_{XL} for aqueous phase, connected in series.

Synthesis of 1,6-Anhydro-2,3,4-tri-*O*-benzyl-β-D-talopyranose (1). 1,6-Anhydro-β-D-talopyranose was prepared from 1,6-anhydro-β-D-galactopyranose[14] by epimerization of the hydroxyl group on C2, which was accomplished by oxidation and subsequent reduction of the hydroxyl group according to the method of Horton et al.[23] with slight modifications. The yield was 42% based on 1,6-anhydro-β-D-galactopyranose (10 g). To a solution of 1,6-anhydro-β-D-talopyranose (2.4 g, 15 mmol) in *N,N*-dimethylformamide (50 mL) were added NaH (1.2 g, 50 mmol) and benzyl bromide (6.0 mL, 50 mmol) with stirring. After 3 h at room temperature, an excess of methanol was added dropwise to the solution. The mixture was concentrated in vacuo and diluted with chloroform and water. The separated chloroform layer was washed with water several times, dried over anhydrous Na_2SO_4, and concentrated in vacuo. The residue was purified by silica gel chromatography twice, followed by preparative HPLC [hexane/ethyl acetate 3/1 (v/v) as eluent] to give colorless viscous **1** in 83% yield. $[\alpha]_D = -18.9°$ (c 1, $CHCl_3$, 25 °C). ^{1}H NMR (400 MHz, $CDCl_3$, δ, ppm): 3.38 (dd, J = 4.39, 1.65 Hz, 1H, H2), 3.66 (dd, J = 4.21, 3.66 Hz, 1H, H4), 3.71 (dd, J = 5.67, 6.59 Hz, 1H, H6$_{exo}$), 4.17 (t, J = 4.39 Hz, 1H, H3), 4.40 (t, J = 4.39 Hz, 1H, H5), 4.56 (dd, J = 12.4, 26.6 Hz, 2H, O4−CH_2Ph), 4.56 (dd, J = 12.4, 16.0 Hz, 2H, O2−CH_2Ph), 4.74 (d, J = 6.96 Hz, 1H, H6$_{endo}$), 4.86 (dd, J = 12.0, 39.4 Hz, 2H, O3−CH_2Ph), 5.40 (s, 1H, H1), 7.24−7.44 (m, 15H, phenyl × 3). ^{13}C NMR (100 MHz, $CDCl_3$, δ, ppm): 65.9 (C6), 71.4 (O2−*C*H_2Ph, O4−*C*H_2Ph), 73.0 (C5), 74.7 (C3), 75.5 (C4, O3−*C*H_2Ph), 77.3 (C2), 99.9 (C1), 127.3−138.9 (phenyl). Anal. Calcd for $C_{27}H_{28}O_5$: C, 74.98; H, 6.53. Found: C, 74.91; H, 6.51.

Scheme 1. Synthesis and Ring-Opening Polymerization of 1



Polymerization. Ring-opening polymerization and copolymerization were carried out by a high-vacuum technique at −60 or −80 °C as described in the literature,[6] except that a magnetic stirring bar was used in the polymerization ampule. Purification and isolation of the resulting polymer also followed a published method[6] to yield homopolymer **2**. ^{1}H NMR (400 MHz, $CDCl_3$, δ, ppm): 3.62 (br, s, H6), 3.77 (br, s, H2), 3.80 (br, s, H3), 3.86 (br, s, H4), 3.91 (br, s, H6′), 4.06 (br, s, H5), 4.45 (s, O3−CH_2Ph), 4.58 (dd, J = 12.4, 27.0 Hz, O2−CH_2Ph), 4.72 (dd, J = 11.8, 175.1 Hz, O4−CH_2Ph), 4.90 (s, H1), 6.97−7.34 (m, phenyl). ^{13}C NMR (100 MHz, $CDCl_3$, δ, ppm): 67.0 (C6), 70.2 (C5), 71.4 (O3−*C*H_2Ph), 73.3 (O2−*C*H_2Ph), 73.7 (C4), 74.1 (O4−*C*H_2Ph), 74.6 (C2), 78.0 (C3), 100.1 (C1), 127.1−139.2 (phenyl).

Debenzylation[1]**.** A solution of **2** (100 mg, M_n = 17 500, M_w/M_n = 2.5) in dry 1,2-dimethoxyethane (3 mL) was dropped into a solution of sodium (0.6 g) in liquid ammonia (50 mL) with stirring at −78 °C under nitrogen. After 1 h at the same temperature, ammonium chloride was added to the solution until the deep blue color disappeared. A small amount of methanol was added, and then the solution was warmed to room temperature to evaporate the ammonia. The residue was diluted with water (50 mL) and chloroform (10 mL). The aqueous layer was washed with chloroform twice and dialyzed with cellulose dialyzer tubing VT803 (Nacalai Tesque, Inc., Japan) against deionized water for a day. The solution was concentrated and freeze-dried to afford **3** (M_n = 10 500, M_w/M_n = 2.6) almost quantitatively. $[\alpha]_D = +62.2°$ (c 1, H_2O, 25 °C). ^{1}H NMR (400 MHz, D_2O, δ, ppm): 3.73 (dd, J = 3.48, 10.43 Hz, 1H, H6), 3.89−3.94 (br, m, 4H, H2−H5), 4.14 (dd, J = 3.39, 7.60 Hz, 1H, H6'), 4.99 (s, 1H, H1). ^{13}C NMR (100 MHz, D_2O, δ, ppm): 68.1 (C2), 69.2 (C6), 72.1 (C5), 72.3 (C4), 72.6 (C3), 102.3 (C1).

Results and Discussion

Synthesis and Polymerization of 1. Although 1,6-anhydrohexose is usually synthesized from the parent hexose, 1,6-anhydro-β-D-talopyranose was prepared from D-galactose via several derivatives by the method of Horton et al. (Scheme 1)[23] due to the low natural abundance of D-talose. Simple benzylation of 1,6-anhydro-β-D-talopyranose with benzyl bromide gave monomer **1**, which was not crystalline, allowing for purification by repeated preparative liquid chromatography. The elemental analysis of **1** was in agreement

Table 1. Ring-Opening Polymerization of 1[a]

entry	PF_5 (mol %)	CH_2Cl_2 (mL)	temp (°C)	time (h)	yield[b] (%)	$M_n \times 10^{-3}$[c]	M_w/M_n[c]	$[\alpha]_D$[d] (deg)
1	5	0.20	−60	2	trace			
2	5	0.20	−60	8	trace			
3	10	0.20	−60	2	8	19.6	2.4	+44.9
4	10	0.20	−60	8	22	17.2	2.8	+44.4
5	10	0.40	−60	8	12	16.7	2.8	+43.6
6	10	0.20	−80	8	19	15.5	2.6	+43.5
7	10	0.20	−60	16	20	16.6	2.6	+44.3
8	10	0.20	−60	32	18	18.0	2.7	+43.5
9	20	0.20	−60	2	15	15.3	2.5	+44.3
10	20	0.20	−60	8	24	9.9	2.8	+44.5
11	20	0.40	−60	8	20	9.5	2.8	+44.0
12	20	0.20	−80	8	22	11.5	2.9	+45.0

[a] Monomer **1**, 200 mg. [b] Methanol-insoluble part. [c] Determined by GPC. [d] Measured in $CHCl_3$ (c 1, 25 °C).

with the calculated one. Any impurity was not detected in the ^1H NMR spectrum.

The ring-opening polymerization of **1** was conducted at −60 and −80 °C in methylene chloride under high vacuum with PF_5 as the initiator and terminated by the small addition of methanol. The solution after polymerization being analyzed by thin-layer chromatography and GPC, only polymers and unreacted monomer **1** were observed, and any oligomeric product was not in the solution. As shown in Table 1, when the concentration of PF_5 was lower than 5 mol % relative to the monomer, a trace amount of polymer was obtained (entries 1 and 2). Increasing the concentration to 10 mol % PF_5 gave polymers with $M_n = 15\,500-19\,600$ in 8 to 22% yields (entries 3−8). At 20 mol % PF_5, the yield was slightly improved, but the M_n of the polymers was decreased (entries 3 and 9, 4 and 10, 5 and 11, 6 and 12). Under these conditions, the ratio of the initiator to the monomer was unexpectedly high for polymerization.

A suitable monomer concentration for acquiring high molecular weights and yields of the polymer was 1.0 g mL^{-1} because a considerable decrease in the yield was observed at a lower monomer concentration of 0.50 g mL^{-1} (entries 4 and 5, 10 and 11). Monomer concentrations higher than 1.0 g mL^{-1} resulted in a viscous solution even before starting polymerization, making it difficult to establish homogeneous conditions, particularly when the initiator was introduced to the monomer solution.

At temperatures higher than about −40 °C, it is known that chain transfers occur frequently, and structurally irregular polymers are formed in the polymerization of other tribenzylated 1,6-anhydrohexopyranoses when PF_5 is used as the initiator.[2,6,8,14−16] Hence, temperatures of −60 and −80 °C were used in the polymerization of the present monomer; no significant differences were not found between polymerization results at these temperatures (entries 4 and 6, 10 and 12).

Polymer Structure. The specific rotations of the polymers ranged from +43° to +45° (Table 1). Such nearly constant values originate from the high stereoregularity on the glycosidic linkages of all the polymers since the specific rotation of carbohydrates is greatly influenced by the configuration of the anomeric carbon according to Hudson's rule.[24] The values of the polymers were positive, whereas that of monomer **1** with a β anomeric configuration was negative as −18.9°, suggesting that every glycosidic linkage of the polymers was in the α anomeric configuration. Figure 2 shows the 100 MHz ^{13}C NMR spectra of **1** and polymer **2,** expanded from 60 to 110 ppm. Each peak was assigned on the basis of the HSQC and HMBC spectra. In the polymer spectrum, the peaks corresponding to each position number, particularly the

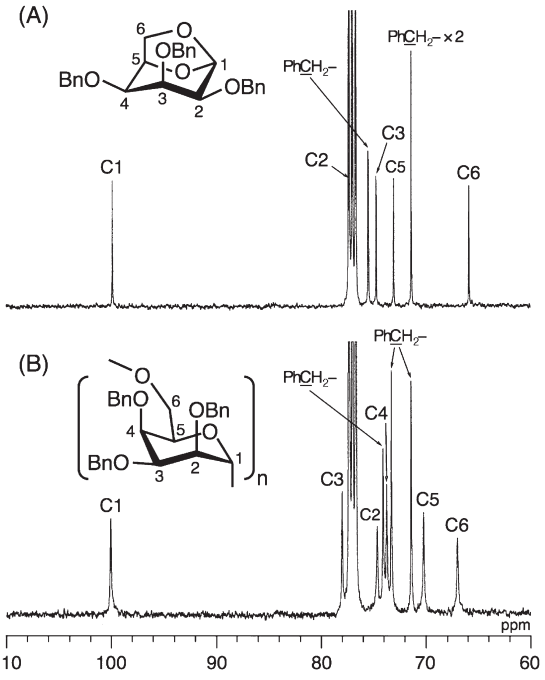


Figure 2. 100 MHz ^{13}C NMR spectra of (A) 1,6-anhydro-2,3,4-tri-*O*-benzyl-β-D-talopyranose (**1**) and (B) 2,3,4-tri-*O*-benzyl-(1→6)-α-D-talopyranan (**2**) in $CDCl_3$.

C1 peak located at 100.1 ppm, were all singlets, confirming that the polymer had only one type of repeating unit and that its stereoregularity on the glycosidic linkages is high.

From these results of the specific rotations and NMR spectra, it was concluded that polymer **2** is a highly stereoregular 2,3,4-tri-*O*-benzyl-(1→6)-α-D-talopyranan.

Polymerizability of 1. Comparing the polymerization results in Table 1 with those of polymerization of other benzylated 1,6-anhydrohexopyranoses, the range in yield and molecular weight of polymer **2** is between those of polymers obtained from the respective benzylates of 1,6-anhydroallopyranose[15] and 1,6-anhydroaltropyranose.[16] Namely, the order of ring-opening polymerizability of the benzylated 1,6-anhydrohexopyranoses studied to date is as follows: Man > Glc > Gal > All > Tal > Alt.

According to the theory of Kobayashi and Schuerch,[20] the most influential factor on the polymerizability of 1,6-anhydrohexopyranoses is the number of axial hydroxyl groups on the monomer. The polymerizability of the Tal monomer had been regarded to be extremely low as that of the Alt monomer because both have only one axial hydroxyl group. The higher polymerizability of Tal compared to that of Alt contradicts this theory. Therefore, other factors appear to affect the polymerizability of Tal, which gave a polymer with a maximum M_n = 19 600. It is known that the equatorial hydroxyl group on C2 in 1,6-anhydrohexoses reduces the steric hindrance of the propagating chain end for monomers attacking from the α side, resulting in enhanced polymerizability.[2] This effect is powerful; it allows the polymerizability of Man to exceed that of the Glc. However, this effect does not explain the higher polymerizability of Tal than Alt as both monomers have an equatorial hydroxyl group on C2.

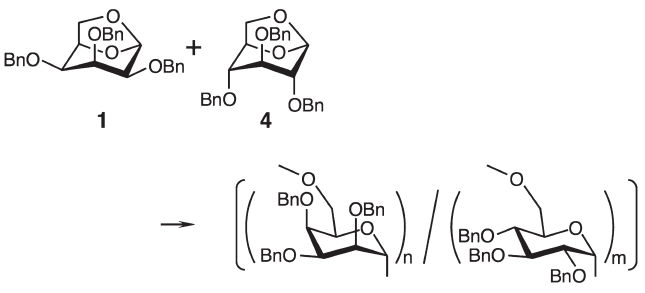
The 1,3-diaxial interaction is another important factor that drives polymerization of 1,6-anhydrohexopyranoses.[20] While there is only one axial hydroxyl group on the Tal monomer, it is on C3 such that three 1,3-diaxial interactions occur between C1 and C3, C3 and C5, and C1 and C5. On the other hand, the Alt monomer, which has one axial hydroxyl

Table 2. Ring-Opening Copolymerization of 1 with 4[a]

entry	mole fraction of **1** in feed (mol %)	PF_5 (mol %)	time (h)	yield[b] (%)	$M_n \times 10^{-3}$[c]	$[\alpha]_D$[d] (deg)	mole fraction of **1** in copolymer[e] (mol %)
1	0	10	0.1	80.4	134	+113.4	0
2	20	10	0.5	12.1	62.5	+82.7	11
3	40	10	1	8.0	34.2	+69.5	21
4	60	10	1	8.0	22.1	+57.1	33
5	80	10	1	7.0	20.3	+50.9	61
6	100	10	1	4.7	17.6	+44.0	100

[a] Total monomers, 400 mg. Solvent, CH_2Cl_2 0.40 mL. Temperature, −60 °C. [b] Methanol-insoluble part. [c] Determined by GPC. [d] Measured in $CHCl_3$ (c 1, 25 °C). [e] Calculated from ^{13}C NMR spectrum.

Scheme 2. Ring-Opening Copolymerization of 1 with 4



group on C4, has only one 1,3-diaxial interaction between C1 and C5. Therefore, Tal appears to possess a more distorted pyranose ring than Alt and thus a higher potential energy for polymerization. When the anhydro ring of 1,6-anhydrohexopyranoses is opened, a conformational change of the pyranose ring from $^1C_4$ to $^4C_1$ takes place to allow bulky hydroxyl groups to occupy the equatorial position.[20] The conformational change varies the number and site of the 1, 3-diaxial interaction; i.e., there is one interaction between C2 and C4 in α-talopyranan and one between C1 and C3 in α-altropyranan. As a result, two 1,3-diaxial interactions are reduced in Tal after ring-opening, whereas the number of interaction in Alt does not change. Thus, we concluded that the primary reason for this higher polymerizability of the Tal monomer, compared to the Alt isomer, is that Tal can produce a much larger enthalpy change due to the larger difference of the number of 1,3-diaxial interaction after polymerization.

Copolymerization of 1. Monomer reactivity ratios are a helpful index for comparing the polymerizability of one monomer with that of another. As shown in Scheme 2, ring-opening copolymerization of **1** with **4**, whose polymerizability is well understood, was attempted in order to derive the reactivity ratios of the monomers. The mole fraction of **1** in the feed was varied by 20 mol %, and each conversion to the polymer was restrained to ∼10% by a shortened polymerization time. Table 2 summarizes the experimental results.

The products are not the mixture of each homopolymer but the copolymers of **1** and **4** because, under the same reaction conditions, homopolymerization of **4** for 0.1 h gave a polymer in 80% yield (entry 1), while copolymerization for even 1 h yielded the products in about 10% yield. The mole fraction of the **1** unit in the copolymer was estimated from the integration ratio of the C1 resonance for the **1** unit to that for the **4** unit in the quantitative ^{13}C NMR spectrum of the copolymer.

Here, the monomer reactivity ratios of r_{Tal} and r_{Glc} are defined as the ratio of the propagation rate constants for the propagating Tal species, that is, $k_{Tal,Tal}/k_{Tal,Glc}$, and for the propagating Glc species, $k_{Glc,Glc}/k_{Glc,Tal}$, respectively. The r_{Tal} and r_{Glc} were calculated using the Kelen−Tüdös method[25,26] to be 0.24 and 2.03, respectively. Comparison with those of the other four benzylated 1,6-anhydrohexopyranoses is shown in Table 3.

The r_{Tal} value of 0.24 was smaller than the r_{All}[15] of 0.44 and considerably larger than the r_{Alt}[16] of 0.06, indicating that the homopolymerizability of the Tal monomer was lower than that of the All monomer but much higher than that of the Alt monomer. These results agree with those obtained by comparing the molecular weight and yield of the resulting homopolymers as described above. On the other hand, $1/r_{Glc}$ represents the ratio of the propagation rate constants for the propagating Glc species, $k_{Glc,Hexose}/k_{Glc,Glc}$. The value of 0.49 for the Tal monomer was larger than that of 0.37 for the All monomer and smaller than that of 0.66 for the Alt monomer. This order can be explained as follows. In the conformational change from $^1C_4$ to $^4C_1$ of the pyranose ring during polymerization, eclipsed conformations between large substituents such as benzyloxy groups on adjacent carbons in the pyranose ring must occur.[2] The activation energy of the propagation must exceed the energies of the eclipsed conformations and that of the steric hindrance of an axial substituent on C2 toward the monomer attacking from the α side. As shown in Table 3, the Tal and All monomers have to pass through three eclipsed conformations on C2−C3, C3−C4, and C4−C5 and on C1−C2, C2−C3, and C3−C4, respectively, so both monomers are expected to need high activation energies for propagation compared with the Alt monomer, which undergoes only one eclipsed conformation on C3−C4. Furthermore, the activation energy of Tal would be lower than that of All due to less steric hindrance of the equatorial benzyloxy group on C2.

Thus, the following conclusions were made concerning the polymerizability of 1,6-anhydrohexopyranoses: (1) The most important factor is the number of axial hydroxyl groups as proposed by Schuerch and Kobayashi. (2) An axial hydroxyl group on C3 is of secondary importance when the numbers of axial hydroxyl groups are the same because the number of 1,3-diaxial interactions decreases greatly after the scission of the 1,6-anhydro ring. (3) While the influence of the number of eclipsed conformations and the steric hindrance of an axial hydroxyl group on C2 are not so powerful, they become significant when the potential energies of the monomers are similar. These conclusions indicate that the two remaining 1,6-anhydrohexopyranoses, the gulose and idose homologues, will not be polymerized at all.

Behavior of PF_5. Uryu et al.[11] investigated the concentration of the initiator for obtaining higher molecular weights in the polymerization of **4**. In general, such initiator concentrations in the polymerization of benzylated 1,6-anhydrohexopyranoses were reported to be less than 1 mol % relative to the monomer.[9−11] The All monomer required exceptionally high concentrations of PF_5 (more than 4 mol %) to produce polymers with high molecular weights,[15] as PF_5 coordinated with not only the oxygen of the 1,6-anhydro ring but also the oxygens of the benzyloxy groups on C2, C3, and C4, as illustrated in Figure 3A.

Similar complexation is likely in the polymerization of **1**. The talopyranosidic residue in polymer **2** adopts a $^4C_1$ conformation, resulting in the formation of the same "axial−equatorial−axial" sequence among the three benzyloxy groups as in the All monomer (Figure 3B). There is much evidence that this type of oxygenic sequence can form relatively stable and reversible complexes with metal ions and/or other Lewis acids.[28−30] We examined the

Table 3. Reactivity Ratios of Copolymerizations of Benzylated 1,6-Anhydrohexoses with 4[a]

hexose	r_{hexose}	r_{Glc}	$1/r_{Glc}$	adjacent carbons[b]	configuration of benzyloxy group on C2
mannose[c]	9.58	0.95	1.05	C2−C3	equatorial
galactose[c]	0.31	1.41	0.71	C1−C2, C3−C4, C4−C5	axial
allose[d]	0.44	2.69	0.37	C1−C2, C2−C3, C3−C4	axial
altrose[e]	0.06	1.52	0.66	C3−C4	equatorial
talose	0.24	2.03	0.49	C2−C3, C3−C4, C4−C5	equatorial

[a] Initiator, PF_5. Solvent, CH_2Cl_2. Temperature, −60 °C. [b] Adjacent carbons which bring eclipsed conformation during conformational change of the pyranose ring. [c] Reference 27. [d] Reference 15. [e] Reference 16.

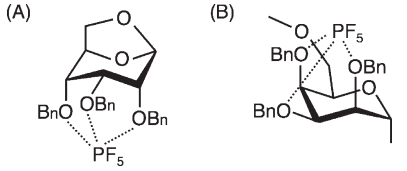


Figure 3. Possible complexation of PF_5 with (A) benzylated 1,6-anhydro-β-D-allopyranose[15] and (B) benzylated (1→6)-α-D-talopyranan (**2**).

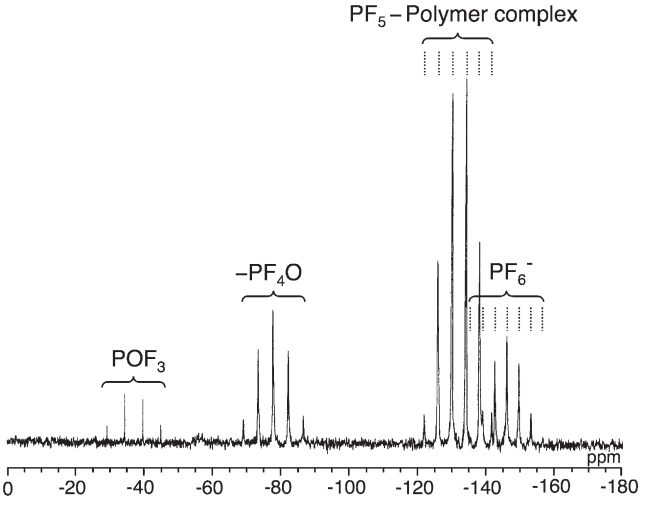


Figure 4. 200 MHz ^{31}P NMR spectrum of the reaction mixture of **1** and PF_5 (5:1) in CD_2Cl_2 at −60 °C. It was measured after 24 h from the mixing.

coordination behavior of PF_5 based on the fact that unexpected large amounts of PF_5 were necessary for the polymerization of **1**. Figure 4 shows the 200 MHz ^{31}P NMR spectrum of the reaction mixture of **1** and PF_5 (10:2) in CD_2Cl_2 at −60 °C, which was measured ~24 h after the polymerization had started.

A narrow quartet at −37 ppm was attributed to POF_3 produced by the reaction of PF_5 with an NMR sample tube made of Pyrex glass.[31] The medium and broad resonances of a quintet at −78 ppm and a septet at −146 ppm were respectively assigned to the $-PFO_4$ group incorporated in the beginning of the polymer chains and the counter anions PF_6^- of the propagating chain ends.[12,32] The strong sextet at −133 ppm is certainly derived from some chemical species including PF_5. However, it is difficult to believe that such a large amount of free PF_5 still existed and that the complex of PF_5 coordinated with the oxygen of the 1,6-anhydro ring in the initiation step still remained without propagation 24 h after the start of the polymerization. Therefore, a possible explanation for the sextet is that considerable amounts of PF_5 were coordinated over the three oxygens of the benzyloxy groups on C2, C3, and C4 of polymer **2**, as shown in Figure 3B. The sextet was peculiar only to the spectrum in the polymerizations of **1** and the All monomers and not observed

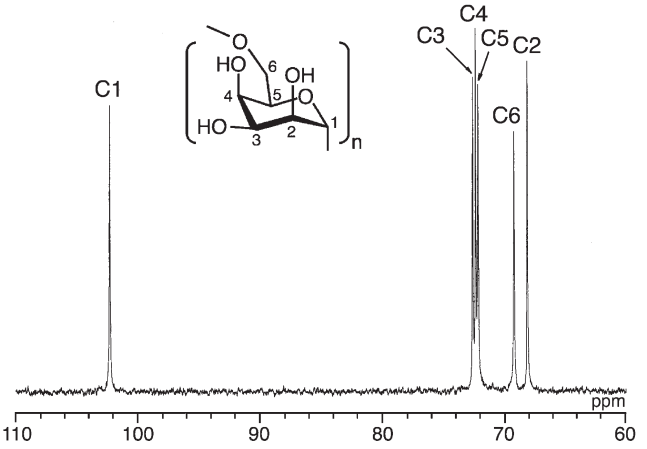


Figure 5. 100 MHz ^{13}C NMR spectrum of (1→6)-α-D-talopyranan (**3**) in D_2O.

in the polymerization of **4**.[12] This complexation would prevent PF_5 from working as the initiator for polymerization of **1** and explains the need for large amounts of PF_5.

Debenzylation of 2. Removal of the benzyl groups of **2** was carried out typically with sodium in liquid ammonia. Interestingly, the resulting new polysaccharide (1→6)-α-D-talopyranan (**3**), as well as the glucan and mannan[34] homologues, was soluble in water, while the galactan[14] and allan[15] homologues were water-insoluble. Those solubilities will depend on the pattern of hydrogen bonds rather than on the molecular weight of each polysaccharide because cellulose, (1→4)-β-D-glucopyranan, has highly regular networks of hydrogen bonds and becomes water-insoluble from only the octamer.[33] Figure 5 is the 100 MHz ^{13}C NMR spectrum of **3** in D_2O. The peak assignments were achieved by the corresponding HSQC and DQF COSY spectra. Only six peaks derived from the talopyranosidic repeating unit appeared, showing no irregular structures and elimination of all benzyl groups. The molecular weight distribution increased slightly from 2.5 to 2.6, most likely due to the tiny scission of glycosidic linkages during debenzylation.

Conclusions

In this study, 1,6-anhydro-2,3,4-tri-*O*-benzyl-β-D-talopyranose, the sixth benzylated 1,6-anhydrohexopyranose, was polymerized to obtain polymers with M_n = 15 500−19 600 in 8−22% yields. The specific rotations and NMR spectra of the resulting polymers revealed that the polymers have a high stereoregularity on the glycosidic linkages. Comparing the monomer reactivity ratios, which derived from copolymerization with the glucose homologue, with those of other benzylated 1, 6-anhydrohexopyranoses, it was found that the polymerizability of the present monomer was between those of the allose and altrose homologues. Such polymerizability would be originated mainly from the axial benzyloxy group on C3 and three 1, 3-diaxial interactions between C1 and C3, C3 and C5, and C1

and C5. ^{31}P NMR spectra during polymerization disclosed that considerable amounts of the initiator coordinated with not only the oxygen of 1,6-anhydro ring of the monomer but also those of the polymer. This additional coordination of the initiator with the polymer oxygens caused the requirement of large amounts of the initiator for polymerization. Debenzylation of the resulting polymer gave a new stereoregular polysaccharide, (1→6)-α-D-talopyranan.

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