Selective Synthesis of Polysaccharide Macromers by Ring-Opening Polymerization of Anhydro Sugar

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ABSTRACT: Two kinds of stereoregular polysaccharide macromers were prepared by cationic ring-opening polymerization of a 1,4-anhydro sugar. 1,4-Anhydro-2,3-bis(*O-tert*-butyldimethylsilyl)-α-D-ribopyranose was polymerized by acryloyl (or methacryloyl) chloride–silver hexafluorophosphate or –silver hexafluoroantimonate complex catalyst to afford (1→5)-α-D-ribofuranan macromer or (1→4)-β-D-ribopyranan macromer bearing an acryloyl (or methacryloyl) terminal group. The macromer was radically polymerized and copolymerized with methyl methacrylate. Desilylation of the copolymer gave polyribose-grafted poly(methyl methacrylate). The mechanism of the selective ring-opening polymerization was discussed from the viewpoint of the roles of the silyl group, the carbenium ion, and the gegenanion.

Stereoregular polysaccharides have been synthesized by ring-opening polymerization of anhydro sugars.[1,2] By sulfation of (1→5)-α-linked polyxylose and polyribose, highly anticoagulant polysaccharides have been obtained.[3] Higher anticoagulant activity seems to require higher stereoregularity of the synthetic polysaccharides. Recently, we found that sulfated xylofuranan and ribofuranan show a unique biological function to inhibit the infection of AIDS (aquired immune deficiency syndrome) virus.[4]

Heparin, which is a natural anticoagulant polysaccharide bearing sulfate and carboxyl groups, occurs as a proteoglycan in which a polypeptide composed of serines and glycines is a trunk polymer and the polysaccharide is a graft polymer.[5] Thus, one can expect to obtain polymeric materials with anticoagulant activity by grafting an active polysaccharide onto synthetic polymers and to use them for a biomedical purpose. For such polysaccharide graft polymers, uses for affinity chromatography are also expected.

In polysaccharide synthesis by ring-opening polymerization, various Lewis acids are used as catalysts, and the structure of the catalyst plays an important role for controlling polymer stereoregularity.[6] 1,4-Anhydro sugars can be polymerized into two kinds of stereoregular polysaccharides with a (1→5)-α-furanose structure having five-membered rings or a (1→4)-β-pyranose structure having six-membered rings.[7] So far, a cellulose-type polysaccharide, i.e., (1→4)-β-glycopyranan, can be obtained only from 1,4-anhydro-α-D-ribopyranose derivatives.[6] Other 1,4-anhydro sugars such as 1,4-anhydro-α-D-xylopyranose,[8] -α-D-lyxopyranose,[9] -α-L-arabinopyranose,[10] -α-D-glucopyranose,[11] and -α-D-galactopyranose[11] all can be polymerized to afford (1→5)-α-furanan-type polysaccharides by ring-opening polymerization but not to give (1→4)-β-pyranan-type ones.

Previously, we have reported the graft polymerization of a 1,6-anhydro sugar onto a polymer.[12] However, the removal of protective benzyl groups from the graft copolymer was too difficult to give a free polysaccharide graft. On the other hand, the graft polymerization of a synthetic monomer onto a synthetic polysaccharide has successfully been performed.[13]

In this study, we report the synthesis of macromers with stereoregular polysaccharide chains by selective ring-opening polymerization of a 1,4-anhydro-α-D-ribopyranose derivative. For this purpose, a catalyst system, which can cause stereoregular polymerization and introduce a double bond to the obtained polysaccharide terminal, is used. In addition, to easily remove protective groups from the polymer, we chose the *tert*-butyldimethylsilyl group for protecting the OH group.

Moreover, it is reported that two possible methodologies for the selective ring-opening polymerization can be accomplished by selection of catalyst systems applicable to the same 1,4-anhydro sugar. Acryloyl chloride–silver hexafluoroantimonate and acryloyl chloride–silver hexafluorophosphate catalyze polymerization of the 1,4-anhydroribose derivative to provide (1→4)-β-D-ribopyranan and (1→5)-α-D-ribofuranan with acryloyl terminals, respectively.

Results and Discussion

Polymerizability of 1,4-Anhydro-2,3-bis(*O-tert*-butyldimethylsilyl)-α-D-ribopyranose (ADSR). ADSR showed high reactivity to such Lewis acids as phosphorus pentafluoride, antimony pentafluoride, and boron trifluoride etherate and also to trifluoromethanesulfonic anhydride to provide high molecular weight polymers. The results of polymerizations are outlined in Table I.

A polymer with high molecular weight ($\bar{M}_n = 21 \times 10^4$) was obtained within a relatively short polymerization time (1 h) with 1 mol % of PF_5 in high yield (88%). Boron trifluoride etherate showed high catalytic activity, giving a polymer with the highest $\bar{M}_n$, 29×10^4. Catalysts antimony pentachloride and trifluoromethanesulfonic anhydride gave low yields. It has been reported that $BF_3 \cdot OEt_2$ affords the highest molecular weight polymers in ring-opening polymerization of a benzylated or methylated 1,4-anhydroribopyranose.[6] In the case of ADSR, however, the high molecular weight was accomplished with Lewis acids such as PF_5 and $SbCl_5$ as well as $BF_3 \cdot OEt_2$.

Taking into account high reactivity of the monomer and easy removal of the group, which will be described later, the *tert*-butyldimethylsilyl group is an excellent hydroxyl-protective group for the polymerization of 1,4-anhydro sugars. The silyl group has been successfully used for the protection of a hydroxyl group in the synthesis of prostaglandin E_2[14] and for the protection of a phenolic hydroxyl group in the anionic polymerization of 4-hydroxystyrene.[15] The silyl group was easily removed from the polymers *tert*-butyldimethylsilylated (1→6)-α-D-glucopyranan[16] and (1→5)-α-L-arabinofuranan.[10b]

Polymer structure was examined by optical rotation and ^{13}C NMR spectroscopy. All the polymers showed high positive specific rotations ranging from +79.9° to +103.7°, indicating a high proportion of an α-configuration. The ^{13}C NMR spectrum of a polymer having $[\alpha]_D$ +97.6° indicates a high stereoregularity. The C1 carbon absorption appears at 102.9 ppm, which corresponds to a (1→5)-α-D-ribofuranosidic unit. A small peak due to the C1 carbon is also seen at 107.8 ppm, which corresponds to a (1→4)-β-D-ribopyranosidic unit. In theory, there are four

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Table I
Polymerization of 1,4-Anhydro-2,3-bis(*O-tert*-butyldimethylsilyl)-α-D-ribopyranose[a]

	catalyst							
no.	kind	mol %	temp, °C	time, h	yield, %	$[\alpha]_D^{25}$,[b] deg	$10^{-4}\bar{M}_n$[c]	α-content, %
1	PF_5	1	−60	1.0	88.2	+96.0	21.2	91.1
2	PF_5	2	−60	1.0	82.2	+97.0	10.2	91.7
3	PF_5	5	−60	24.5	50.8	+82.0	0.85	79.6
4	$SbCl_5$	2	−60	5.8	51.1	+79.9	11.3	77.5
5	$BF_3{\cdot}OEt_2$	4	0	0.5	88.8	+97.6	26.9	92.4
6	$BF_3{\cdot}OEt_2$	4	−60	1.0	80.4	+103.7	24.7	93.8
7	$BF_3{\cdot}OEt_2$	4	−78	1.0	92.5	+98.6	28.6	91.5
8	$(CF_3SO_3)_2O$	8	−60	48.0	10.0	+94.3	nd[e]	nd[e]

[a] Monomer, 0.3 g; methylene chloride, 0.6 mL. [b] Measured in chloroform (*c* 1%). [c] Determined by GPC. [d] Calculated by ^{13}C NMR spectroscopy. [e] Not determined.

Table II
Polymerization of 1,4-Anhydro-2,3-bis(*O-tert*-butyldimethylsilyl)-α-D-ribopyranose with Acid Chloride–Silver Salt Complex Catalyst[a]

	complex catalyst								
no.	acid chloride	silver salt	monomer concn, w/v %	temp, °C	time, h	yield, %	$[\alpha]_D^{25}$,[b] deg	$10^{-3}\bar{M}_n$[c]	polym struct[d]
1	$CH_2{=}CHCOCl$	$AgPF_6$	25	0	3.0	74	+33.5	8.2	
2	$CH_2{=}CHCOCl$	$AgPF_6$	10	−40	1.0	64	+91.0	113	α-F
3	$CH_2{=}CHCOCl$	$AgSbF_6$	25	0	2.0	72	+13.9	9.1	β-P
4	$CH_2{=}CHCOCl$	$AgSbF_6$	10	−20	1.0	61	+15.1	7.8	β-P
5	$CH_2{=}C(CH_3)COCl$	$AgPF_6$	20	0	1.0	81	+56.1	15	
6	$CH_2{=}C(CH_3)COCl$	$AgPF_6$	20	−20	1.0	87	+57.1	18	
7	$CH_2{=}C(CH_3)COCl$	$AgSbF_6$	10	−40	1.0	64	+19.3	11	β-P
8	$CH_2{=}C(CH_3)COCl$	$AgSbF_6$	50	−40	1.0	75	+94.4	127	α-F
9	$CH_2{=}CHC_6H_4CH_2Cl$	$AgPF_6$	25	0	7.0	72	+83.0	5.6	α-F
10	$CH_2{=}CHC_6H_4CH_2Cl$	$AgPF_6$	50	−40	2.5	88	+87.5	6.0	α-F
11	$CH_2{=}CHC_6H_4CH_2Cl$	$AgSbF_6$	50	−40	3.5	82	+95.5	7.4	α-F
12	CH_3CH_2COCl	$AgPF_6$	50	−40	1.0	73	+101.4	54	α-F
13	$CH_3(CH_2)_2COCl$	$AgPF_6$	50	−40	2.0	60	+101.1	44	α-F
14	$CH_3(CH_2)_4COCl$	$AgPF_6$	50	−40	4.0	81	+104.2	27	α-F

[a] Monomer, 0.5 g; solvent, methylene chloride; catalyst concentration, 10 mol %. [b] Determined in chloroform (*c* 1%). [c] Determined by GPC. [d] α-F = (1→5)-α-D-ribofuranan; β-P = (1→4)-β-D-ribopyranan.

possible structural units in polyriboses obtained by cationic ring-opening polymerization of 1,4-anhydro-α-D-ribopyranose (=1,5-anhydro-β-D-ribofuranose). However, in the previous reports,[6,7] two structural units, (1→4)-β-D-ribopyranosidic and (1→5)-α-D-ribofuranosidic units, were found in polyriboses obtained by the ring-opening polymerization.

For the polymer having $[\alpha]_D$ +97.6°, the content of the (1→5)-α-configuration was estimated from the C1 carbon absorption to be 92.4%. When other Lewis acids and trifluoromethanesulfonic anhydride were employed as the catalyst, polymers so obtained showed α-contents of 79.6–93.8%. Therefore, it was concluded that these catalysts cause mainly 1,5-ring scission of the silylated monomer to produce (1→5)-α-D-ribofuranan. This tendency is similar to the cases in benzylated 1,4-anhydro-α-D-ribopyranose,[6] 1,4-anhydro-α-D-xylopyranose,[8] and 1,4-anhydro-α-D-lyxopyranose.[9] These monomers afforded mainly or exclusively the (1→5)-α-linked furanose structure. A model compound, 2,7-dioxabicyclo[2.2.1]heptane, which also showed a tendency for a linkage of a 1,5-anhydro ring, is cleaved to open and give a polymer composed of five-membered rings.[17]

For the silylated monomer, the mechanism of polymerization leading to the 1,5-linked polymer is assumed to be the same as that considered for the benzylated anhydroribose.[6] We could consider that the opening of the 1,5-anhydro ring in the silylated monomer is largely due to bulkiness of the *tert*-butyldimethylsilyl group, which can prevent Lewis acid from complexing with the 1,4-linked oxygen.

Selective Ring-Opening Polymerization of ADSR by Complex Catalysts into Macromers. To prepare a macromer, we sought an initiator including a C=C double bond. Olah and co-workers reported the synthesis of stable (alkyloxy)carbenium ion by reacting acyl fluoride with Lewis acid fluoride.[18] Schuerch and co-workers used it for polymerization.[19] Extending this method, we used (ethenyloxy)carbenium instead of (alkyloxy)carbenium ion. When (ethenyloxy)carbenium prepared by reacting acryloyl chloride with silver hexafluorophosphate according to eq 1 was used as the initiator, ADSR was polymerized

$$CH_2{=}CHCOCl + AgPF_6 \rightarrow CH_2{=}CHCO^+PF_6^- + AgCl \qquad (1)$$

in a fairly high yield. The results of polymerization are summarized in Table II.

The polymer obtained by the $CH_2{=}CHCO^+PF_6^-$ complex catalyst at −40 °C showed a high α-stereoregularity ($[\alpha]_D$ +91.0°) and a high molecular weight ($\bar{M}_n = 113 \times 10^3$; no. 2 in Table II). From the fact that neither acryloyl chloride nor silver hexafluorophosphate can initiate the polymerization of ADSR, it is obvious that the generated (ethenyloxy)carbenium catalyzes the polymerization. The terminal acryloyl group attached to poly(ADSR) was detected by ^1H NMR, as shown in Figure 1A. Small absorptions due to methylene and methine protons appeared at 5.8, 6.1, and 6.4 ppm.

A methacryloyl chloride–silver hexafluorophosphate complex catalyst also gave a poly(ADSR) with $[\alpha]_D$ +57° and $\bar{M}_n = 18 \times 10^3$ in 87% yield (no. 6). In the ^1H NMR spectrum of the polymer, absorptions due to the methacryloyl group as well as those due to the polymer backbone were observed (Figure 1B). Clearly from the specific rotation of +57°, the α-stereoregularity of the polymer seemed not so high.

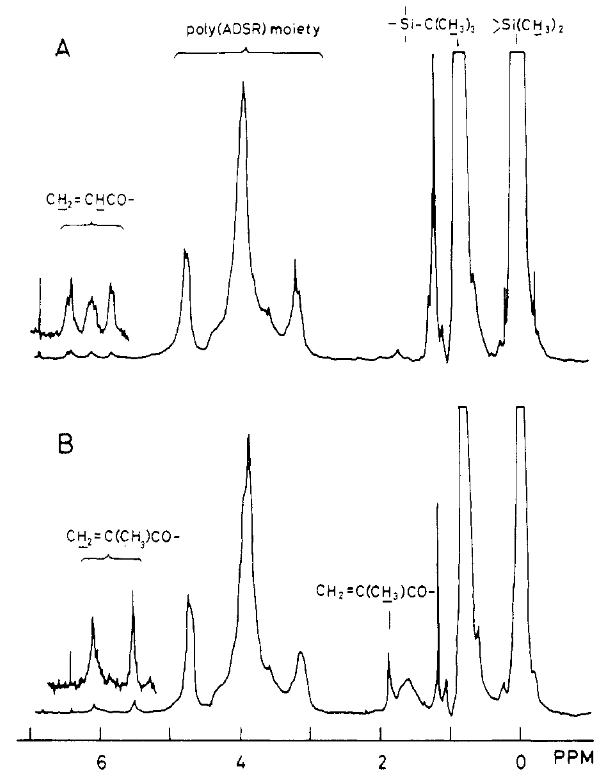


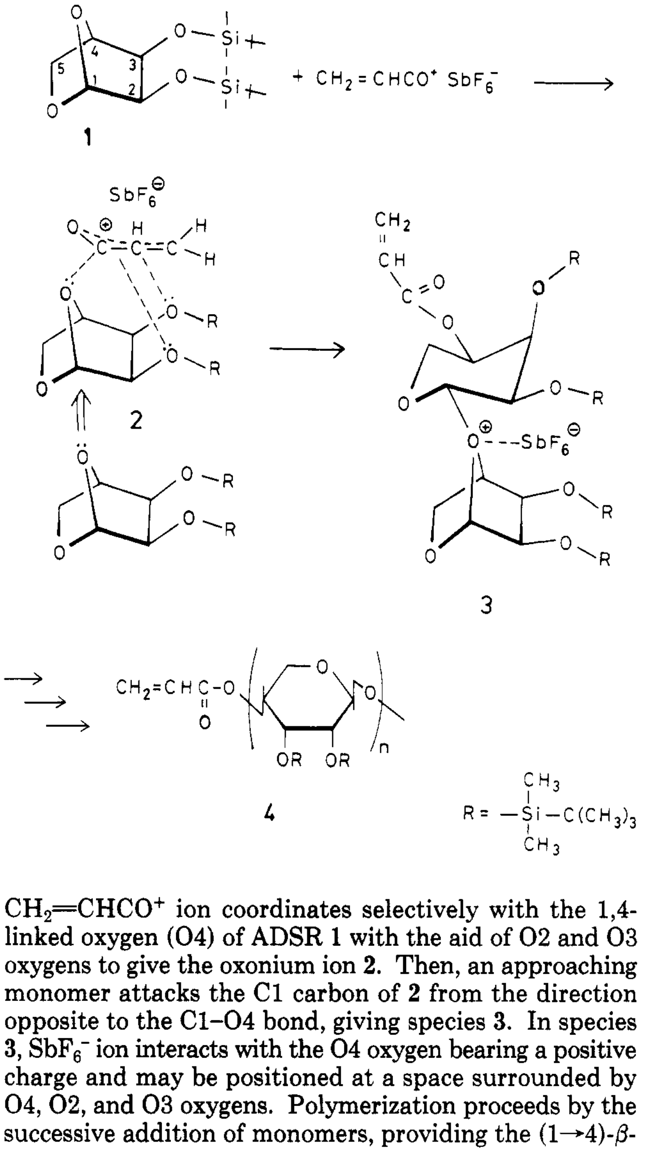
Figure 1. ^1H NMR spectra of poly(ADSR) macromers polymerized with (A) acryloyl chloride–$AgSbF_6$ complex at 0 °C and (B) methacryloyl chloride–$AgSbF_6$ complex at -40 °C (solvent $CDCl_3$).

On the other hand, $CH_2{=}CHCO^+SbF_6^-$ and $CH_2{=}C(CH_3)CO^+SbF_6^-$ as catalysts afforded polymers with small and positive specific rotations, i.e., +14°–+19° (no. 3, 4, and 7). All the ^{13}C NMR spectra of polysaccharides with or without protecting groups revealed that the polymers had the (1→4)-β-D-ribopyranan structure. Monomer concentration also affected stereoregulation, leading to the β-pyranose structure. At 10–25% monomer concentrations, the β-pyranose structure was formed, while at 50% the α-furanose structure was obtained under similar conditions (Table II, no. 8). A cellulose-type polysaccharide, (1→4)-β-D-ribopyranan, has been synthesized so far by the ring-opening polymerization of 1,4-anhydro-2,3-O-alkylidene-α-D-ribopyranose[5,20] and 1,4-anhydro-2,3-di-O-methyl-α-D-ribopyranose.[6] This means that the present one provides a third synthetic methodology of the cellulose-type polysaccharide. However, the kind of sugar is still limited to D-ribose.

Even if the same carbenium ion was used as an initiating cation for the polymerization of ADSR, by employment of different gegenanions such as PF_6^- and SbF_6^- the two different kinds of selective ring-opening polymerizations occurred. A similar result has been already observed in the polymerization of 1,4-anhydro-2,3-di-O-methyl-α-D-ribopyranose, in which the catalysts were PF_5 and $BF_3 \cdot OEt_2$, and the respective gegenanions PF_6^- and BF_4^-.[6]

Both (chloromethyl)styrene–$AgPF_6$ and –$AgSbF_6$ complex catalysts yielded poly(ADSR)s with high 1,5-α-furanose contents (no. 9 and 10). When saturated acid chloride–$AgPF_6$ complexes were used, the obtained poly(ADSR)s had the (1→5)-α-ribofuranan structure (no. 12–14). This finding revealed that both the structure of the carbenium ion and the kind of gegenanion play a decisive role in the formation of the two stereoregular macromers.

Scheme I
Proposed Mechanism for (1→4)-β-D-Ribopyranan Macromer



The mechanism leading to the formation of (1→4)-β-D-ribopyranan macromer is assumed to follow Scheme I. $CH_2{=}CHCO^+$ ion coordinates selectively with the 1,4-linked oxygen (O4) of ADSR 1 with the aid of O2 and O3 oxygens to give the oxonium ion 2. Then, an approaching monomer attacks the C1 carbon of 2 from the direction opposite to the C1–O4 bond, giving species 3. In species 3, SbF_6^- ion interacts with the O4 oxygen bearing a positive charge and may be positioned at a space surrounded by O4, O2, and O3 oxygens. Polymerization proceeds by the successive addition of monomers, providing the (1→4)-β-ribopyranan macromer 4.

The mechanism affording (1→5)-α-D-ribofuranan may be the same as that for the benzylated monomer,[6] that is, (1) the carbenium ion binds to the 1,5-linked oxygen and (2) PF_6^- ion then coordinates with the 1,5-linked oxygen.

^{13}C NMR spectra of (1→5)-α-D-ribofuranan and (1→4)-β-D-ribopyranan, which were obtained by desilylating the corresponding 2,3-bis(*O-tert*-butyldimethylsilyl)ated polysaccharides (no. 12 and 4 in Table II), are shown in Figure 2. Each polymer contained a small amount of isomeric units, which were determined from C1 absorptions appearing at 104 (α-furanose) and 109 ppm (β-pyranose). The former was composed of 93% 1,5-α-ribofuranosidic and 7% 1,4-β-ribopyranosidic units, while the latter was composed of 10% 1,5-α-ribofuranosidic and 90% 1,4-β-ribopyranosidic ones.

Polymerization of the Macromer into a Polysaccharide Graft Copolymer. Acryloyl-terminal and methacryloyl-terminal macromers were polymerized by a radical initiator and copolymerized with methyl methacrylate (MMA) to give graft copolymers; the results are summarized in Table III.

When an acryloyl-terminal macromer with $\bar{M}_n$ = 7800 was polymerized by azobisisobutyronitrile catalyst, a copolymer with $\bar{M}_n$ = 38000 was obtained in 49% conversion of the macromer (no. 1 in Table III). Since a gel per-

Table III
Copolymerization of Poly(ADSR) Macromer (M_2) with Methyl Methacrylate (M_1)[a]

		M_2 feed			graft polymer				
no.	M_1, wt %	wt %	type[b]	$10^{-3}\bar{M}_n$	conversion (M_2), %	$10^{-3}\bar{M}_n$	ADSR,[c] mol %	trunk PMMA $\overline{DP}_n$	no. of branches
1	0	100	A	7.8	49	38	100	0	4.8
2	67	33	A	7.8	44	78	9	570	2.7
3	0	100	M	15	53	43	100	0	2.9
4	50	50	M	11	26	53	12	350	1.6

[a] Solvent, toluene; catalyst, azobisisobutyronitrile (1 wt %); temperature, 60 °C; time, 24 h. [b] A = acryloyl-terminal macromer; M v methacryloyl-terminal macromer. [c] Determined from the ^{1}H NMR spectrum of deprotected graft polymer.

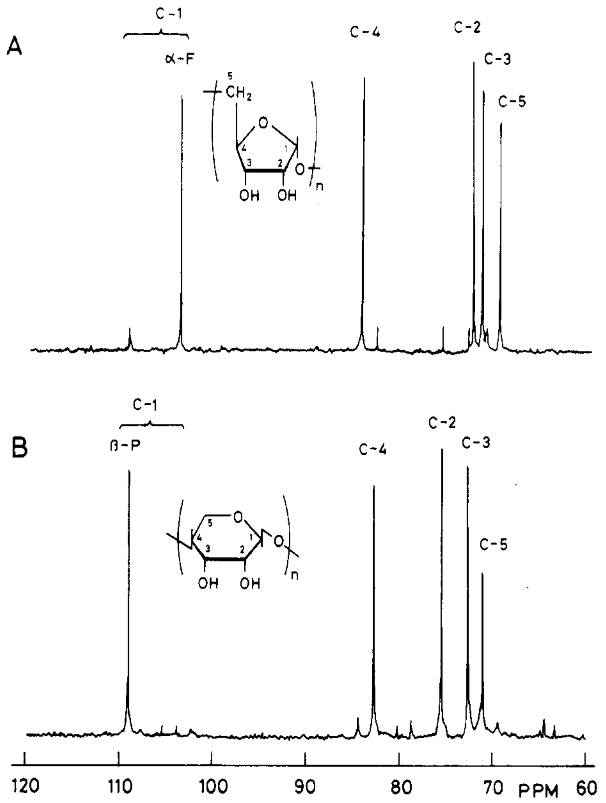


Figure 2. ^{13}C NMR spectra of desilylated polyriboses: (A) (1→5)-α-D-ribofuranan obtained by propionyl chloride–$AgPF_6$ complex; (B) (1→4)-β-D-ribopyranan obtained by acryloyl chloride–$AgSbF_6$ complex (solvent D_2O).

meation chromatogram of the product polymer exhibited a bimodal molecular weight distribution ascribable to the starting macromer and the produced graft copolymer, the conversion and the molecular weight were calculated from gel permeation chromatography (GPC).

Its copolymerization with MMA gave a copolymer with $\bar{M}_n$ = 78 000, which is composed of a trunk poly(methyl methacrylate) (PMMA) with $\overline{DP}_n$ = 570 and a graft polyribose derivative with $\overline{DP}_n$ = 22. The average number of branches per polymer was 2.7.

A methacryloyl-terminal macromer with $\bar{M}_n$ = 15 000 was polymerized into a copolymer with $\bar{M}_n$ = 43 000 in 53% conversion (no. 3), while a methacryloyl-terminal macromer with a very high molecular weight (127 × 10^3) exhibited almost no polymerizability. The copolymerization with MMA gave a copolymer with $\bar{M}_n$ = 53 000, but the conversion was low (26%). This polymer was a graft copolymer composed of a trunk PMMA with $\overline{DP}_n$ = 350 and a graft polyribose derivative with $\overline{DP}_n$ = 30.

Desilylation was carried out on a mixture of poly(MMA-*g*-ADSR) and unreacted poly(ADSR) macromer by use of $(n\text{-Bu})_4NF$, giving a mixture of poly(MMA-*g*-ribose) and polyribose. Since poly(MMA-*g*-ribose) was insoluble in water and polyribose was soluble in water, separation and purification of poly(MMA-*g*-ribose) was performed by using a dimethylformamide–water system. In Figure 3, the ^{1}H NMR spectrum of poly(MMA-*g*-ribose) is shown along with that of a mixture of poly(MMA-*g*-ADSR) and poly(ADSR) macromer. The graft copolymer had 12 mol % (1→5)-α-D-ribofuranan branches. The polysaccharide portion was estimated on a desilylated graft copolymer by ^{1}H NMR spectroscopy.

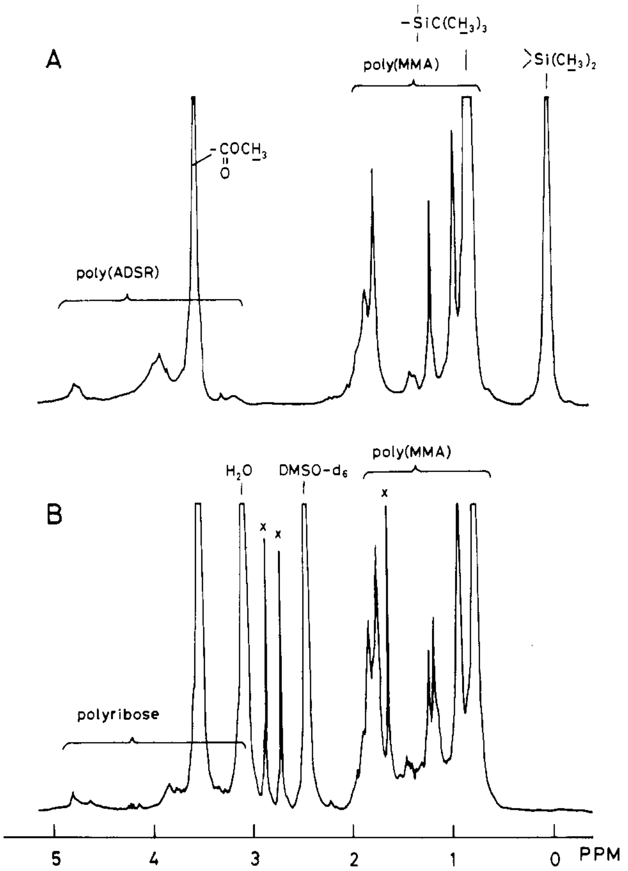


Figure 3. ^{1}H NMR spectra of (A) a mixture of poly(MMA-*g*-ADSR) and poly(ADSR) macromer (solvent $CDCl_3$) and (B) poly(MMA-*g*-ribose) (x, impurity; solvent DMSO-d_6).

Experimental Section

Synthesis of 1,4-Anhydro-2,3-bis(*O*-*tert*-butyldimethylsilyl)-α-D-ribopyranose (ADSR). 1,4-Anhydro-α-D-ribopyranose was prepared by pyrolyzing 150 g of D-ribose under vacuum according to the method of Köll et al.[21] The pyrolysis was repeated five–seven times. The yield of crude crystals of the anhydro sugar was 7%. To a solution of 1,4-anhydro-α-D-ribopyranose (0.92 g) dissolved in 10 mL of tetrahydrofuran were added 2.8 mL of pyridine and 3.6 g of silver nitrate and then 3.2 g of *tert*-butyldimethylchlorosilane at room temperature by employing a modified method of Hakimelahi et al.[22] The reaction mixture was stirred at room temperature overnight and filtered. The filtrate was mixed with aqueous sodium bicarbonate, and the resulting aqueous solution was extracted with chloroform; the extract was combined and concentrated. The residue was purified by silica gel chromatographic technique eluting with 4:1 (by volume) *n*-hexane–ethyl acetate; mp 47.0–48.0 °C (uncorrected); $[\alpha]_D{}^{25}$ –34.6° (*c* 1%, $CHCl_3$). NMR assignments were carried out by 2D NMR measurements: ^1H NMR (ppm) H1 (5.31 (s)), H2 (3.94 (d)), H3 (3.99 (d)), H4 (4.55 (d)), H5 (3.42 (quartet)), H5′ (3.34 (d)), *t*-Bu (0.93), Si–Me (–0.02); ^{13}C NMR (ppm) C1 (101.87), C2 (76.43), C3 (74.34), C4 (80.63), C5 (64.00), *t*-Bu (25.68), Si–Me (–4.72, –5.33).

Polymerization. ADSR monomer was polymerized with a Lewis acid catalyst under high vacuum ($\sim 10^{-5}$ mmHg) by using a glass polymerization apparatus equipped with breakseals similar to that described in the literature.[23] Each polymerization was performed at a scale of 0.3 g of monomer. When an acid chloride–silver salt complex was used as the catalyst, a glass polymerization apparatus equipped with an acid chloride ampule and a silver salt dropping ampule was employed. ADSR in the polymerization ampule was dissolved in methylene chloride, which was transferred by distillation from the solvent ampule, followed by vacuum distillation of an acid chloride into the polymerization ampule. Then, the ampule was melted and cleaved from the vacuum line and kept at a constant temperature. The silver salt was dropped into the solution, and the solution was vigorously shaken for a few minutes. Polymerization was terminated by the addition of methanol. The mixture was dissolved in chloroform, and silver chloride filtered off. The chloroform solution was neutralized with sodium bicarbonate, washed with water, dried over sodium sulfate, and concentrated. The solution was poured into methanol to precipitate the polymer. Purification was carried out by dissolution–reprecipitation three times by using a chloroform–methanol system, and the polymer was freeze–dried from benzene.

Polymerization and Copolymerization of Poly(ADSR) Macromer. Poly(ADSR) macromer (0.2 g) having an acryloyl or methacryloyl group was polymerized with azobisisobutyronitrile (2 mg) in 1 mL of toluene at 60 °C for 24 h under vacuum. After the reaction, the polymer was dissolved in chloroform and precipitated from methanol. Purification was performed by dissolution–reprecipitation by using chloroform–methanol three times, and the polymer was finally freeze-dried from benzene. Copolymerization of poly(ADSR) with methyl methacrylate was performed in a similar way.

Removal of the *tert*-Butyldimethylsilyl Group from the Graft Polymer. To a tetrahydrofuran solution of poly(MMA-*g*-ADSR) was added a 1 M tetra-*n*-butylammonium fluoride solution in tetrahydrofuran, followed by refluxing for 2 h with stirring. The reaction was terminated by addition of water. The precipitated polymer was dissolved in dimethylformamide and reprecipitated from water. The purification was repeated three times. The polymer was dried under reduced pressure.

Measurements. ^1H (270 MHz) and ^{13}C (67.8 MHz) NMR spectra were measured by using a JEOL JMN GX-270 spectrometer. Specific rotation was measured by means of a Perkin-Elmer 241 polarimeter. The molecular weight of tetrahydrofuran-soluble and water-soluble polymers was determined by using Toyo Soda Model 802UR and Model HLC-803D gel permeation chromatographs with standard polystyrene and standard dextran as references, respectively.

Registry No. ADSR, 114958-30-4; MMA, 80-62-6; $CH_2{=}CHCOCl$, 814-68-6; $CH_2{=}C(CH_3)COCl$, 920-46-7; $CH_2{=}CHC_6H_4CH_2Cl$, 30030-25-2; CH_3CH_2COCl, 79-03-8; $CH_3CH_2CH_2COCl$, 141-75-3; $CH_3(CH_2)_4COCl$, 142-61-0; $AgPF_6$, 26042-63-7; $AgSbF_6$, 26042-64-8; D-ribose, 50-69-1; 1,4-anhydro-α-D-ribopyranose, 114958-31-5.

References and Notes

(1) Schuerch, C. *Adv. Carbohydr. Chem. Biochem.* 1981, *39*, 157.

(2) Uryu, T. In *Models of Biopolymers by Ring-Opening Polymerization*; CRC Press: New York, in press.

(3) Hatanaka, K.; Yoshida, T.; Miyahara, S.; Sato, T.; Ono, F.; Uryu, T.; Kuzuhara, H. *J. Med. Chem.* 1987, *30*, 810.

(4) Nakashima, H.; Yoshida, O.; Tochikura, T. S.; Yoshida, T.; Mimura, T.; Kido, Y.; Motoki, Y.; Kaneko, Y.; Uryu, T.; Yamamoto, N. *Jpn. J. Cancer (Gann)* 1987, *78*, 1164.

(5) Robinson, H. C.; Horner, A. A.; Höök, M.; Ögren, S.; Lindahl, U. *J. Biol. Chem.* 1978, *253*, 6687.

(6) Uryu, T.; Yamanouchi, J.; Kato, T.; Higuchi, S.; Matsuzaki, K. *J. Am. Chem. Soc.* 1983, *105*, 6865.

(7) Uryu, T.; Kitano, K.; Ito, K.; Yamanouchi, J.; Matsuzaki, K. *Macromolecules* 1981, *14*, 1.

(8) Uryu, T.; Yamanouchi, J.; Hayashi, S.; Tamaki, H.; Matsuzaki, K. *Macromolecules* 1983, *16*, 320.

(9) Hagino, A.; Yoshida, S.; Shinpuku, T.; Matsuzaki, K.; Uryu, T. *Macromolecules* 1986, *19*, 1.

(10) (a) Koyama, Y.; Harima, K.; Matsuzaki, K.; Uryu, T. *J. Polym. Sci., Polym. Chem. Ed.* 1985, *23*, 2989. (b) Yoshida, T.; Kida, M.; Uryu, T. *Polym. J.* 1987, *19*, 915.

(11) Uryu, T.; Yamaguchi, C.; Morikawa, K.; Terui, K.; Kanai, T.; Matsuzaki, K. *Macromolecules* 1985, *18*, 599.

(12) Uryu, T.; Hagino, A.; Terui, K.; Matsuzaki, K. *J. Polym. Sci., Polym. Chem. Ed.* 1981, *19*, 2313.

(13) Chen, Y.-Y.; Oshima, R.; Hatanaka, K. Uryu, T. *J. Polym. Sci., Polym. Chem. Ed.* 1986, *24*, 1539.

(14) Corey, E. J.; Venkateswarlu, A. *J. Am. Chem. Soc.* 1972, *94*, 6190.

(15) Hirao, A.; Takenaka, K.; Packirisamy, S.; Yamaguchi, K.; Nakahama, S. *Makromol. Chem.* 1985, *186*, 1157.

(16) Uryu, T.; Yamanaka, M.; Henmi, M.; Hatanaka, K.; Matsuzaki, K. *Carbohydr. Res.* 1986, *157*, 157.

(17) Hall, H. K.; DeBlauwe, F.; Carr, L. J.; Rao, V. S.; Reddy, G. S. *J. Polym. Sci., Polym. Symp.* 1976, *No. 56*, 101.

(18) Olah, G. A.; Kuhn, S. J.; Tolgyesi, W. S.; Baker, E. B. *J. Am. Chem. Soc.* 1962, *84*, 2733.

(19) Uryu, T.; Schuerch, C. *Macromolecules* 1971, *4*, 342.

(20) Uryu, T.; Kato, T.; Higuchi, S. *Sen-i Gakkaishi* 1984, *40*, T-439.

(21) Köll, P.; Deyhim, S.; Heyns, K. *Chem. Ber.* 1973, *106*, 3565.

(22) Hakimelahi, G. H.; Proba, Z. A.; Oglivie, K. K. *Tetrahedron Lett.* 1981, *22*, 4775.

(23) Ruckel, E. R.; Schuerch, C. *J. Org. Chem.* 1966, *31*, 2233.