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Polymerization of vinyl sugar ester using ascorbic acid and hydrogen peroxide as a redox reagent

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Abstract

Radical polymerization of water-soluble vinyl sugar esters was examined using ascorbic acid and hydrogen peroxide to produce hydroxyl radical as a radical initiator in water. Vinyl sugar ester having non-reducing sugar, 6-*O*-vinyladipoyl α-methyl D-glucoside, was polymerized at lower polymer yield under air atmosphere than that under vacuum condition. Ascorbic acid also reacts with oxygen molecules under air atmosphere to produce superoxide, which is well known as an effective scavenger of hydroxyl radical, so the hydroxyl radical generated with hydrogen peroxide is wasted by reaction with the superoxide. On the other hand, vinyl sugar ester having reducing sugar moiety, 6-*O*-vinyladipoyl D-glucose, was polymerized by the redox initiator not only under vacuum condition but also under air atmosphere. It was assumed from the consideration and the result that reducing sugar moiety of 6-*O*-vinyladipoyl D-glucose is involved in the polymerization under air atmosphere.

Keywords: Redox reagent; Vinyl sugar; Ascorbic acid; Fenton reagent

1. Introduction

Synthesis of glycopolymer is an interesting field and many reports have been published. Most glycopolymers reported previously have poly(acrylate) or poly(styrene) as backbones (Miyata & Nakamae, 1997). However poly(vinyl ester)-type glycopolymers have distinctive characteristics of biodegradability and biocompatibility, little attention has been devoted to them. In the recent years, several groups have reported synthesis of poly(vinyl ester)-type glycopolymers and their functions. Miura, Wada, Nishida, Mori, and Kobayashi (2004) examined the synthesis of glycoconjugate polymers with poly(vinyl ester) backbones and the polymer showed inhibition against Shiga toxin-1. Wu, Lu, Xiao, Yao, and Lin (2004) reported the anomer and regio-selective synthesis of vinyl sugar ester catalyzed by protease. Albertin, Kohlert, Stenza, Foster, and Davis (2004) reported the controlled radical polymerization of vinyl sugar ester to get a polymer having a narrow-polydispersity.

To develop a biodegradable sugar branched polymer, we have been examined enzymatic synthesis of vinyl sugar ester involving vinyl ester, adipic acid ester and sugar moiety (Kitagawa & Tokiwa, 1998) and their chemical polymerization (Kitagawa, Takegami, & Tokiwa, 1998). The obtained polymers showed biodegradability (Tokiwa et al., 2000). We previously reported that the sugar ester was polymerized easily with Fenton reagent in water (Kitagawa et al., 1998). Redox catalyzed polymerizations using ferrous ion and peroxidative compound have been reported to be useful for grafting reaction of natural fiber such as chitosan (Lagos & Reyes, 1988), wool (Misra, Singha, & Sharma, 1982), arginic acid (Shah, Patel, & Trivedi, 1994) and linen (Das, Mohanty, & Singh, 1989). Ascorbic acid is also used instead of the ferrous ion (Larpent & Tadros, 1991). Ascorbic acid is reported to produce activated oxygen under mild condition, and recently it is used for linear polymer synthesis of sugar alcohol derivatives containing vinyl group (Miura, Ikeda, & Kobayashi, 2003). These catalysts, which promote the reaction under room temperature, atmospheric pressure, neutral pH and water as a solvent, have attracted considerable interest as an environmentally friendly method.

In the present study, the polymerization of the vinyl sugar ester using ascorbic acid and hydrogen peroxide as a redox initiator in water was investigated.

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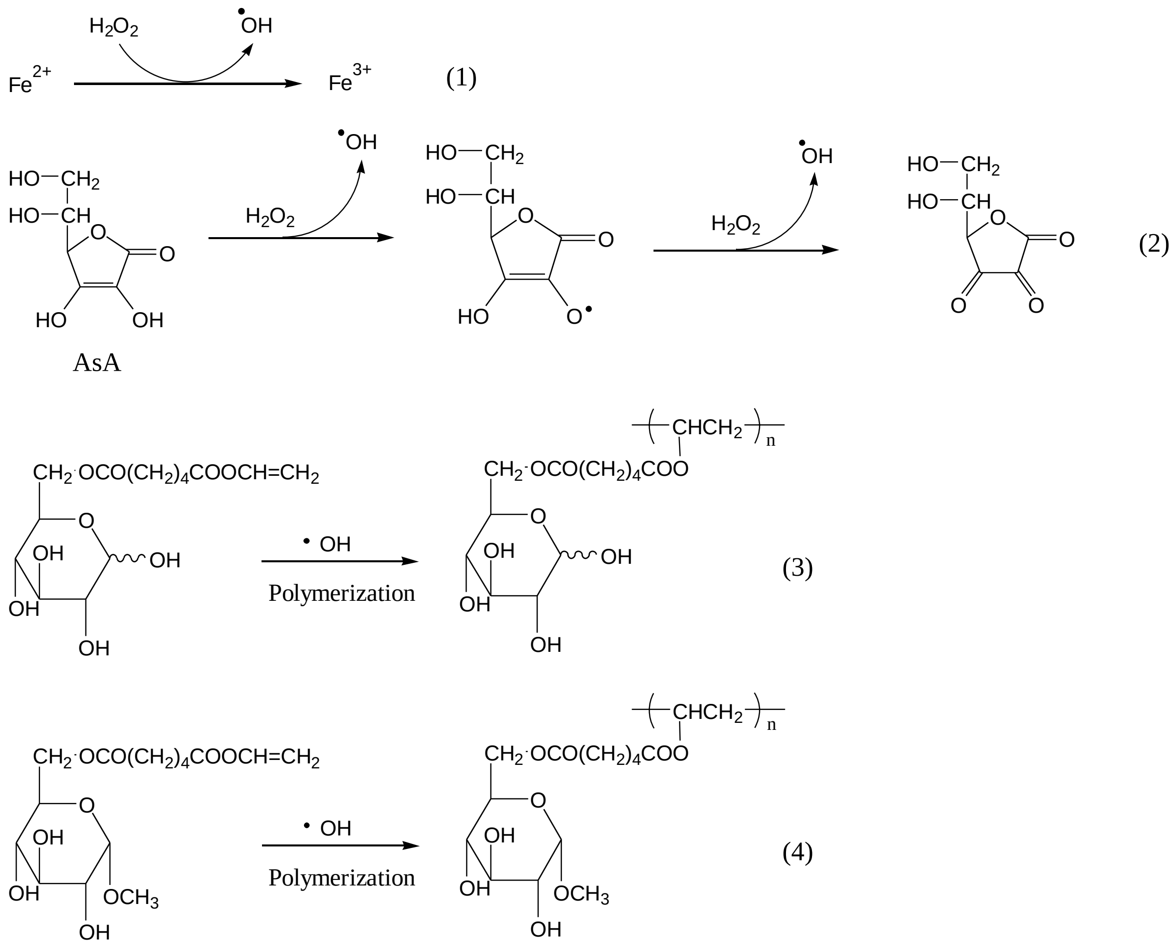

Fig. 1. Radical polymerization of vinyl sugar ester by redox reagent.

2. Experimental part

2.1. Materials

Vinyl sugar esters, 6-*O*-vinyladipoyl D-glucose and 6-*O*-vinyladipoyl α-methyl D-glucoside, were synthesized by the enzymatic method according to our previously reported method (Kitagawa & Tokiwa, 1998; Kitagawa et al., 1999). Ascorbic acid, ferrous sulfate and hydrogen peroxide were from Wako Pure Chemical Ind. Ltd.

2.2. Analytical methods

The polymer structures were established by ^{13}C NMR (JEOL:JNM-EX270). Molecular weight of polymer was determined by gel permeation chromatography (GPC) with refractive index detector (TOSOH). Analysis columns, TSK α-M and α-3000 (TOSOH), were used with a mobile phase of 0.1 M NaCl at a flow rate of 1.0 ml/min. Poly(ethylene oxide)(molecular weight fraction from 26,000 to 920,000, TOSOH) and poly(ethylene glycol)(molecular weight fraction 600–20,000, Wako Pure Chemical Ind. Ltd.) were used as molecular weight standards.

2.3. Polymerization of sugar ester

The polymerization of 6-*O*-vinyladipoyl D-glucose by ascorbic acid–hydrogen peroxide was carried out as follows: in a 10 ml glass tube, a mixture containing 6-*O*-vinyladipoyl D-glucose (0.5 g), and 2 ml of water containing 10 mM ascorbic acid and 7 mM hydrogen peroxide was maintained at 25 °C for 15 h under high vacuum (freeze–evacuate–thaw method was used to degass the solvent completely) or under air atmosphere. The resulting product was precipitated in acetone and dried under reduced pressure at 40 °C.

The polymerization of 6-*O*-vinyladipoyl D-glucose by Fenton reagent was carried out as follows: in a 10 ml glass tube, a mixture containing 6-*O*-vinyladipoyl D-glucose (0.5 g), and 2 ml of water containing 0.02% ferrous sulfate and 7 mM hydrogen peroxide was maintained at 25 °C for 15 h under high vacuum or under air atmosphere. The resulting product was precipitated in acetone and dried under reduced pressure at 40 °C. ^{13}C NMR (DMSO-d6) of poly(6-*O*-vinyladipoyl D-glucose): δ 23.70, 23.90, 32.92,33.30 ($-CH_2-$), 63.90 (C-6α,C-6β), 69.00 (C-5α), 70.14 (C-4α), 70.48 (C-4β), 72.04 (C-2α), 72.79 (C-3α), 73.39 (C-5β), 74.57 (C-2β), 76.28 (C-3β), 92.15 (C-1α), 96.76 (C-1β), 171.92, 172.63 (C=O).

Table 1
Molecular weights of the polymers on the polymerization of 6-*O*-vinyladipoyl D-glucose and 6-*O*-vinyladipoyl α-methyl D-glucoside in water using redox initiators

Sugar monomer	Catalyst	Condition	M_w	M_n	M_w/M_n
6-*O*-vinyladipoyl D-glucose	AsA–H_2O_2	Vacuum	39,900	25,800	1.5
		Air	31,300	18,500	1.7
	Fe^{2+}–H_2O_2	Vacuum	66,400	31,300	2.1
		Air	38,500	21,900	1.8
6-*O*-vinyladipoyl α-methyl D-glucoside	AsA–H_2O_2	Vacuum	75,400	39,400	1.9
		Air	63,300	36,000	1.8
	Fe^{2+}–H_2O_2	Vacuum	110,000	40,100	2.7
		Air	99,000	40,000	2.5

The polymerization of 6-*O*-vinyladipoyl α-methyl D-glucoside was performed under conditions identical to those of 6-*O*-vinyladipoyl D-glucose. ^{13}C NMR (DMSO-d6) of poly(6-*O*-vinyladipoyl α-methyl D-glucoside): δ 23.81, 23.90, 33.05, 33.30 (–CH_2–), 54.29 (OCH_3), 63.67 (C-6), 69.49 (C-5), 70.44 (C-4), 71.77 (C-2), 73.21 (C-3), 99.61 (C-1), 172.00, 172.54 (C=O).

3. Results and discussion

Fenton's reagent is well known for its ability to effect vinyl polymerization. The mechanism by which Fenton's reagent participates in the chain reaction was elucidated by hydroxyl radical formed by interaction of hydrogen peroxide and secondary ferrous ion is responsible for initiating vinyl polymerization as shown in Fig. 1 (1). Ascorbic acid also reacts with hydrogen peroxide and produces hydroxyl radical, and initiates polymerization in Fig. 1 (2). These reactions proceed under room temperature in harmless water, and vinyl sugar esters, 6-*O*-vinyladipoyl D-glucose or 6-*O*-vinyladipoyl α-methyl D-glucoside, would be polymerized by the produced hydroxyl radical (Fig. 1 (3, 4)).

Fig. 2 shows the effect of air atmosphere on polymerization by a redox reagent such as Fenton's reagent or ascorbic acid–hydrogen peroxide. The polymerization condition showed in the experimental part. Generally oxygen existing in the reaction mixture serves as a polymerization inhibitor. In the case of non-reducing sugar derivative, 6-*O*-vinyladipoyl α-methyl D-glucoside, polymerization by both catalysts was inhibited in the presence of oxygen as a radical capture under air atmosphere and produced polymer at low yield compared with the yield under vacuum condition. On the other hand, reducing sugar derivative, 6-*O*-vinyladipoyl D-glucose, preceded the polymerization even under air atmospheric condition, almost to the same as under vacuum condition. Table 1 shows the molecular weights of the obtained polymers on the above polymerization reaction revealed in Fig. 1. Molecular weights on the polymerization under air atmosphere were lower than those under vacuum condition, and molecular weights of poly(6-*O*-vinyladipoyl α-methyl D-glucoside) were higher than those of poly(6-*O*-vinyladipoyl D-glucose).

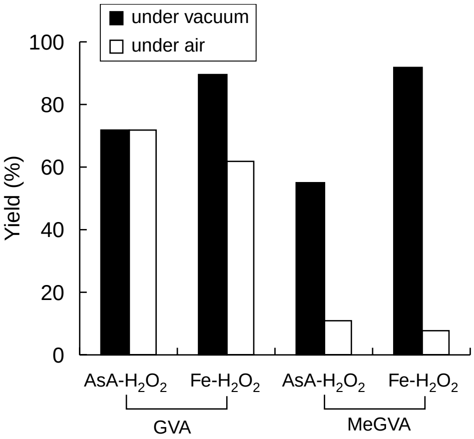

Fig. 2. Polymerization of 6-*O*-vinyladipoyl D-glucose (GVA) and 6-*O*-vinyladipoyl α-methyl D-glucoside (MeGVA) in water using ascorbic acid–hydrogen peroxide (AsA–H_2O_2) and/or ferrous sulfate-hydrogen peroxide (Fe–H_2O_2).

Polymerization of 6-*O*-vinyladipoyl D-glucose under air atmosphere showed unique results, and the reaction catalyzed by ascorbic acid and hydrogen peroxide was examined in detail. Fig. 3(A) shows the effect of concentration of ascorbic acid as radical initiator on the polymerization of 6-*O*-vinyladipoyl D-glucose in water under air atmosphere in the presence of 7 mM hydrogen peroxide. An increase in ascorbic acid concentration parallels an increase in polymer yield, and reached a plateau at more than 10 mM. The molecular weight of the polymer decreased at the concentration of 100 mM ascorbic acid. Fig. 3(B) shows the effect of concentration of hydrogen peroxide on the polymerization of 6-*O*-vinyladipoyl D-glucose with ascorbic acid (10 mM) in water under atmosphere. The polymer yield decreases with an increase in hydrogen peroxide concentration. Further increasing hydrogen peroxide concentration at more than 28 mM did not promote polymerization and the molecular weights of the polymers also decreased. It is thought that the molecular weight of the polymer decreased by use of too much radical initiator because

Table 2
Effect of reaction temperature on the polymerization of 6-*O*-vinyladipoyl D-glucose using ascorbic acid and hydrogen peroxide in water under atmosphere

Temperature (°C)	Yield (%)	M_w	M_n	M_w/M_n
25	79	48,300	25,800	1.9
35	81	43,000	25,300	1.7
45	82	40,500	23,200	1.7
55	72	32,000	18,600	1.7

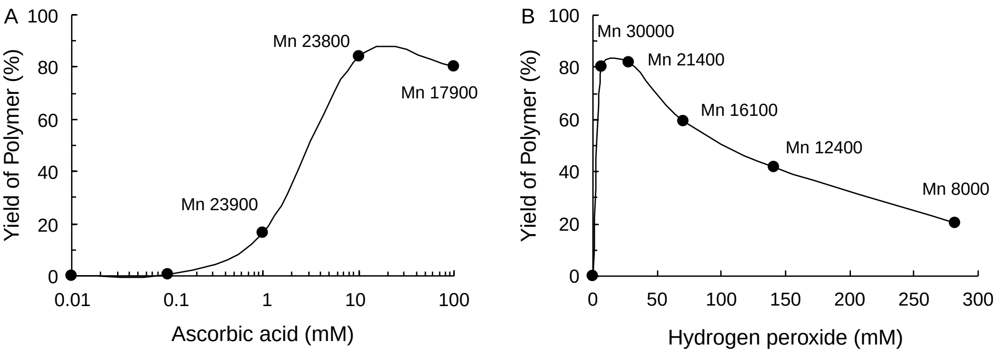

Fig. 3. Effect of concentration of ascorbic acid (A) and hydrogen peroxide (B) as radical initiators on the polymerization of 6-*O*-vinyladipoyl D-glucose in water under atmosphere.

the monomer was exhausted by the initiation reaction of polymerization and was reduced for elonging reaction. Further, it is suggested that the produced polymer might be degraded by hydroxyl radicals as described in our previous report (Kitagawa et al., 2001).

Table 2 shows the effect of reaction temperature on the polymerization of 6-*O*-vinyladipoyl D-glucose using ascorbic acid (10 mM) and hydrogen peroxide (7 mM) in water under air atmosphere. Although the yields did not change significantly, molecular weights of the polymers depend on the reaction temperature, and the optimum temperature for maximum molecular weight was 25 °C similar to general redox reagent.

The influence of reaction time on the polymerization of 6-*O*-vinyladipoyl D-glucose using ascorbic acid (10 mM) and hydrogen peroxide (7 mM) in water under air atmosphere is shown in Fig. 4. The polymerization finished in less than 1 h. Hydroxyl radical has higher reactivity, so it seems that the polymerization proceeded as soon as the radical generated. Polymer yield was calculated from the resulting product's weight precipitated in acetone. The oligomer soluble in the solvent was not recovered from the reaction mixture. Hence, quantitative yield of polymer was not obtained but the yield was about 70–80% in these experiments.

It is known that ascorbic acid and/or Fe^{2+} react with oxygen molecules and produce superoxide under air atmosphere (Fig. 5 (1, 2)). Superoxide is well known as an effective scavenger of hydroxyl radical, and the hydroxyl radical is wasted by reaction with these superoxides. (Fig. 5 (3)). Hence, in the case of the polymerization of 6-*O*-vinyladipoyl α-methyl D-glucoside under air atmosphere, hydroxyl radical was scavenged by the superoxide, and the polymerization carried out at lower yield. In the case of 6-*O*-vinyladipoyl D-glucose, polymerization occurred even under air atmosphere similar to under vacuum condition, but produced polymer of lower molecular weight. Polymerizable sugar esters are present in the reaction mixture at a higher concentration. So it is possible that the reducing sugar moiety of 6-*O*-vinyladipoyl D-glucose is related to the reaction of activated oxygen species.

Kashimura et al. studied the autoxidation of reducing sugars such as sugar phosphates (Morita, Kashimura, & Komano, 1982), aldopentoses (Kashimura et al., 1982), and oxidized polysaccharides (Morita et al., 1982). It is known that enediol derivatives react with hydrogen peroxide or oxygen molecules and produce hydroxyl radicals or

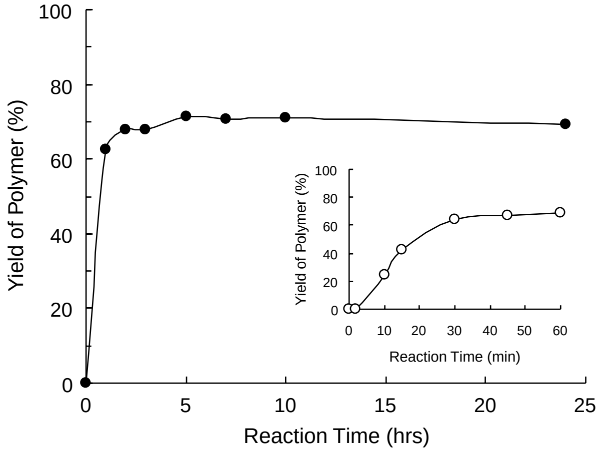

Fig. 4. Time course of polymerization of 6-*O*-vinyladipoyl D-glucose using ascorbic acid and hydrogen peroxide as radical initiators in water under atmosphere.

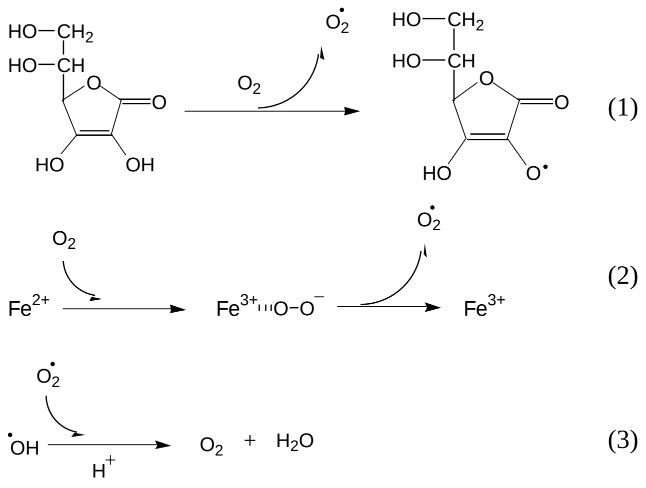

Fig. 5. Superoxide generation with ascorbic acid or Fe^{2+} under air atmosphere.

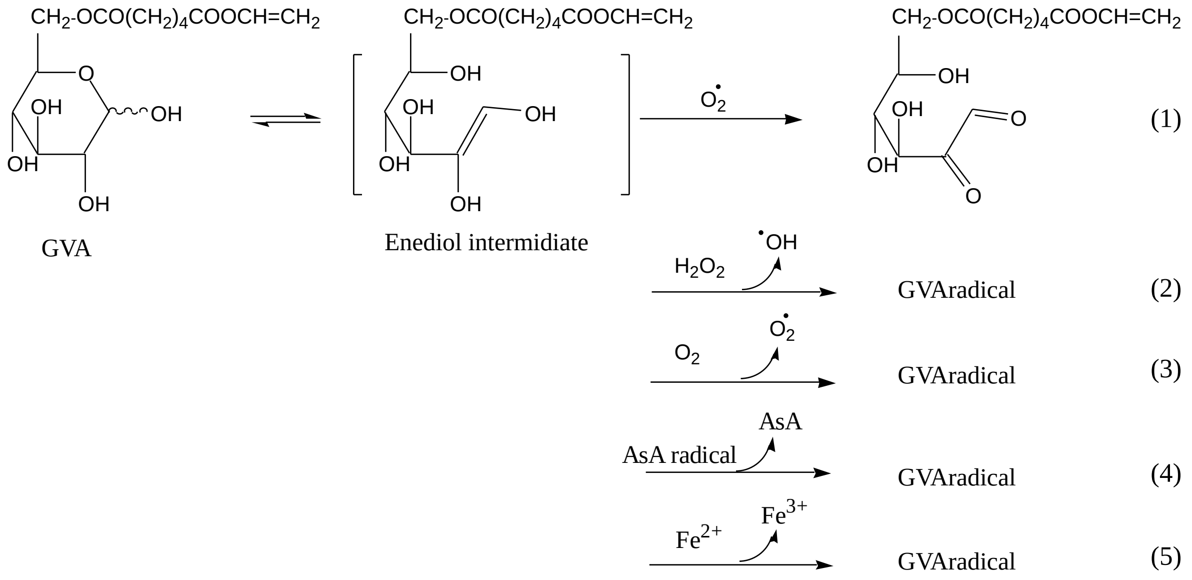

Fig. 6. Reaction of 6-*O*-vinyladipoyl D-glucose (GVA) with oxygen and activated oxygen species.

superoxide, and further that the enediol moiety scavenges superoxide (Isbell, 1976). The reducing sugar moiety of 6-*O*-vinyladipoyl D-glucose has an enediol structure. In the present reaction condition, the polymerizable reducing sugar ester is also expected to react with superoxide, hydrogen peroxide and oxygen molecules, and scavenge and/or produce activated oxygen species as shown in Fig. 6. On the other hand, non-reducing sugar ester, 6-*O*-vinyladipoyl α-methyl D-glucoside, does not react with these molecules, because it does not have the enediol moiety. Hemiacetal OH group of reducing sugar ester seems to be involved in the complexed polymerization reaction under air atmosphere. It is thought that under air atmosphere, enough hydroxyl radical, which could polymerize, was generated on the reaction of 6-*O*-vinyladipoyl D-glucose. Furthermore it is probable that ascorbic acid radical and Fe^{3+} may permit one electron reduction by reducing moiety of 6-*O*-vinyladipoyl D-glucose (Fig. 6 (4, 5)).

4. Conclusion

We examined the polymerization in water and used two types of sugar monomers, 6-*O*-vinyladipoyl D-glucose and 6-*O*-vinyladipoyl α-methyl D-glucoside, which polymerized by hydroxyl radicals via redox reaction. By the polymerization using 6-*O*-vinyladipoyl α-methyl D-glucoside, polymer was obtained in vacuum condition at the higher yield than that under air atmosphere. While by the polymerization using 6-*O*-vinyladipoyl D-glucose, polymer was obtained not only in vacuum but also under air atmosphere at almost similar manner. The structural difference between two monomers is 1-position of glucose moiety, that is, reducing sugar moiety of 6-*O*-vinyladipoyl D-glucose must be involved in the reaction of redox reagents in the presence of oxygen.

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