Polymerization of Bicyclic Acetals. 7. Stereoregulation in the Cationic Polymerization of 6,8-Dioxabicyclo[3.2.1]octane Initiated with Boron Trifluoride Etherate

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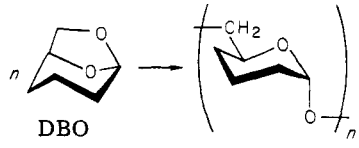
ABSTRACT: The dyad tacticity of the polymers obtained in the cationic ring-opening polymerization of 6,8-dioxabicyclo[3.2.1]octane (DBO) under various conditions (solvent—toluene, methylene chloride, and 1-nitropropane; initiator—boron trifluoride etherate; temperature −90–0 °C) was estimated by means of ^{13}C-NMR spectroscopy. The isotactic dyad content was found to depend markedly upon the polymerization temperature, varying from 84% for the polymer obtained in methylene chloride at −90 °C to 48% for the polymer prepared in the same solvent at 0 °C. The solvent effect on the stereoregularity of the polymer was not appreciable. In order to clarify the origin of the steroregulation, D,L copolymerization of monomer mixtures of different optical purities was undertaken in methylene chloride at −78 °C with boron trifluoride etherate as an initiator. Conversion dependence of the specific rotation of the D,L copolymers indicated that the L enantiomer being in excess in the starting monomer mixture was preferentially incorporated into the D,L copolymer chain. It is concluded therefore that the preferred formation of the isotactic dyad sequence along the polymer chain in the cationic polymerization of DBO at lower temperature is primarily due to the stereoregulation displayed by the growing chain end. A possible mechanism for the steric control is proposed.

Ring-opening polymerization of bicyclic acetals containing a tetrahydropyran ring leads to polysaccharide analogues which are of particular interest not only as model compounds for elucidating the elaborate functions of natural polysaccharides in relation to their chemical structures but also as potential materials for biomedical application. From this standpoint, we have been investigating cationic polymerization of several bicyclic acetals and the chemical modifications of the resultant polymers to synthetic polysaccharides and their derivatives.[1-8]



DBO (1)

Polymerization of 6,8-dioxabicyclo[3.2.1]octane, which is hereafter referred to as DBO, has been studied by us[1,2] and two other groups[9,10] independently; DBO undergoes cationic polymerization at low temperature to yield a high molecular weight polyacetal having a backbone structure similar to that of dextran, a naturally occurring (1→6)-linked polysaccharide. The present article is concerned with the stereoregulation in the polymerization of DBO initiated with boron trifluoride etherate, as revealed by ^{13}C-NMR analysis of the polymer and D,L copolymerization of monomer mixtures of different optical purities.

There have been numerous publications on the stereospecific ring-opening polymerization of various cyclic monomers including epoxides, episulfides, lactones, and α-amino acid *N*-carboxylic anhydrides.[11-13] Stereospecific polymerizations of these monomers have been achieved, in most cases, with the use of so-called coordinated catalysts and they are interepreted satisfactorily in terms of the enantiomorphic catalyst sites control mechanism.[12] Alternatively, some stereospecific polymerizations, although the number is limited, proceed through the growing chain control mechanism.[12] For example, the polymerization of *tert*-butylethylene oxide by potassium *tert*-butoxide[14,15] and the polymerization of D,L-amino acid *N*-carboxylic anhydrides by trialkyl aluminum[16-18] and primary amines[19-21] can be classified into this category. However, as far as we know, there has been no literature dealing with stereospecific polymerization of cyclic acetals by either of these two mechanisms. This is understandable in view of the fact that cyclic acetals can be polymerized only through cationic mechanism, while stereospecific polymerizations of cyclic monomers reported so far have been performed through anionic or coordinated anionic mechanisms. The present paper describes the first example for stereospecific ring-opening polymerization of cyclic acetals by a conventional cationic initiator.

Experimental Section

Materials. Racemic DBO was prepared from 3,4-dihydro-2*H*-pyran-2-carbaldehyde (acrolein dimer) according to Brown's procedure.[22,23] (+)-(1*R*,5*S*)-DBO (1,6-anhydro-2,3,4-trideoxy-β-L-glycerohexopyranose in the nomenclature of carbohydrate chemistry) was synthesized from sodium 3,4-dihydro-2*H*-pyran-2-carboxylate through the optical resolution using dehydroabietylamine as a resolving reagent.[6] These monomers were purified by stirring their methylene chloride solutions over calcium hydride for a few days at room temperature followed by fractional distillation under reduced pressure. Toluene was washed successively with concentrated sulfuric acid, water, 5% aqueous sodium hydroxide, and finally water and subsequently refluxed over sodium metal and distilled. Methylene chloride was purified by washing with 5% aqueous sodium carbonate and water, followed by refluxing over and distilling with phosphorus pentoxide. 1-Nitropropane was stirred over calcium hydride for several days and fractionally distilled under reduced pressure. Boron trifluoride etherate was freshly distilled before use.

Polymerization Procedure. Polymerization of racemic DBO was carried out in an evacuated sealed glass ampule at temperatures ranging from −90 to 0 °C with the use of boron trifluoride etherate as the initiator. The polymerization procedure has been described in detail in the previous paper.[6] D,L copolymerization of monomer mixtures of different optical purities was carried out similarly in methylene chloride at −78 °C.

Characterization. ^{1}H- and ^{13}C-NMR spectra were recorded at ambient temperature on a JNM-MH-100 spectrometer operating at 100 MHz and a JNM-FX-100 Fourier transform spectrometer operating at 25 MHz, respectively. Deuteriochloroform and tetramethylsilane were used as solvent and internal reference. Number average molecular weight of methanol-soluble polymers was determined with a Hewlett Packard vapor pressure osmometer Model 302 in benzene solutions at 37 °C. Number average and weight average molecular weights of methanol-insoluble polymers were estimated by means of gel permeation chromatography in chloroform with a JASCO

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Table I
Cationic Polymerization of Racemic 6,8-Dioxabicyclo[3.2.1]octane[a]

solvent	temp, °C	convn., %	$M_n \times 10^{-3}$	$M_w \times 10^{-3}$	isotactic dyad, % peak b	peak c	peak e	av	α form, % ^{13}C	^{1}H[b]
CH_2Cl_2	0	54[c]	1.4		47	50	48	48	73	74
CH_2Cl_2	−30	22[c]								77
		23[d]	7.9	8.6	48	54	55	52	77	83
CH_2Cl_2	−60	81[d]	26	58	53	59	59	57	87	88
CH_2Cl_2	−78	95[d]	55	138	73	78	78	75	100	100
CH_2Cl_2	−90	92[d]	129	327	86	83	84	84	100	100
$C_6H_5CH_3$	−90	38[d]	41	178	80	80	79	80	100	100
$C_3H_7NO_2$	−30	36[c]								76
		9[d]	10	13	46	51	48	48	76	78
$C_3H_7NO_2$	−90	88[d]	15	37	79	80	80	80	100	100

[a] Monomer, 1.27–1.44 g; solvent, 4.0 mL; initiator, $BF_3 \cdot Et_2O$, 2 mol %; time, 24 h. [b] Determined by the peak area of the equatorial acetal proton (δ 4.85) relative to the total peak area of the equatorial and axial (δ 4.40) acetal protons.[2] [c] Methanol-soluble polymer. [d] Methanol-insoluble polymer.

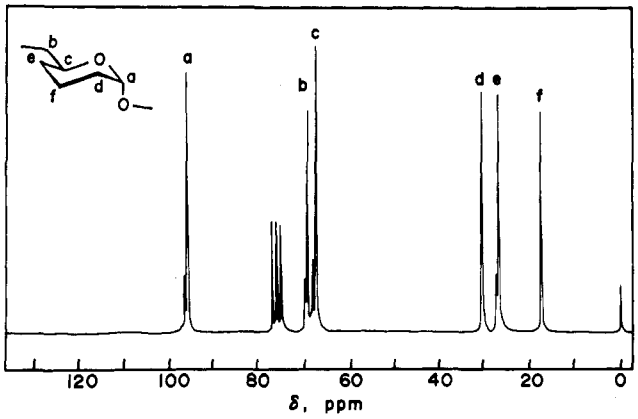


Figure 1. ^{13}C-NMR spectrum of racemic poly(tetrahydropyran-2,6-diyloxymethylene) prepared in methylene chloride at −78 °C. Solvent, $CDCl_3$; concentration, 7%; 25 MHz; internal reference, tetramethylsilane.

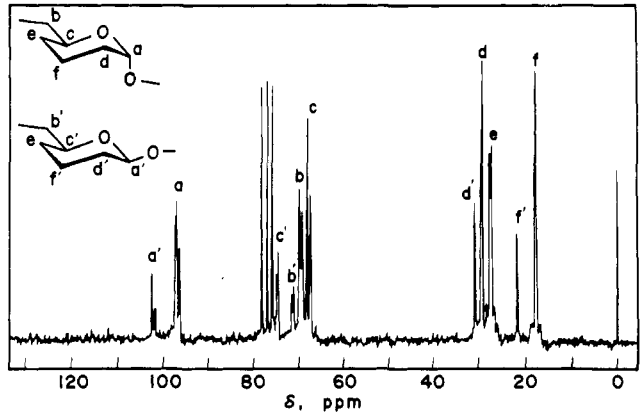


Figure 2. ^{13}C-NMR spectrum of racemic poly(tetrahydropyran-2,6-diyloxymethylene) prepared in 1-nitropropane at −30 °C (methanol-insoluble part). Solvent, $CDCl_3$; concentration, 5%; 25 MHz; internal reference, tetramethylsilane.

TRIROTAR. A calibration curve for poly(DBO) was established beforehand by using several fractionated samples of known molecular weights. Specific rotations of optically active monomer mixtures and their polymers were measured in *n*-hexane and chloroform, respectively, with a JASCO polarimeter model DIP-4.

Results and Discussion

Polymerization of Racemic Monomer. Previous ^{1}H-NMR analysis of poly(DBO) (IUPAC nomenclature, poly(tetrahydropyran-2,6-diyloxymethylene)) has disclosed that the polymers obtained at or below −78 °C entirely consist of the structural unit in which the exocyclic oxygen is oriented axially to the tetrahydropyran ring (eq 1), in other words, the polymers are composed of "α form" in the terminology of carbohydrate chemistry.

Figure 1 shows the ^{13}C-NMR spectrum of the racemic poly(DBO) prepared in methylene chloride at −78 °C by using boron trifluoride etherate as the initiator. The signals were assigned as indicated in the figure.[6] It is noteworthy that the signals a, b, c, and e consist of a pair of peaks of different intensities. The chemical shifts of the higher field peak of each pair and of the signals d and f are in complete agreement with those of the corresponding signals of the optically active polymer from (+)-(1*R*,5*S*)-6,8-dioxabicyclo[3.2.1]octane.[6] In view of the facts that the racemic polymer contains only the "α form", and that no lower field peak is discernible for the methylene carbon atoms, d and f, which are remote from the two asymmetric centers in the repeating unit, the lower field peak of each signal pair can be ascribed reasonably to the dyad structures consisting of the D-L enantiomer pair (syndiotactic dyad) and the higher peak to the dyad structures of D-D and L-L consecutive units (isotactic dyad).

Figure 2 gives the ^{13}C-NMR spectrum of the poly(DBO) prepared in 1-nitropropane at −30 °C, together with the peak assignments. Compared with the spectrum in Figure 1, there appear several additional signals assignable to the structural unit in which the exocyclic oxygen is located in the equatorial position of the tetrahydropyran ring, that is, "β form". The coexistence of the "β form" along with the "α form" makes the ^{13}C-NMR spectrum complicated, particularly in the acetal carbon region.

Figure 3 illustrates the polymerization temperature dependence of the ^{13}C-NMR spectra of the acetal carbon region of the polymers prepared in methylene chloride. The signals appearing at δ 102–103 are assignable to the acetal carbon of the "β form", and those at δ 96–98 to that of the "α form". Apparently, these peaks are affected not only by the dyad sequences of the D and L enantiomeric units but also by the sequences of the α and β forms, although unambiguous assignment of each peak is difficult to make. Therefore, the dyad tacticity of poly(DBO) was estimated from the three sets of the signals b, c, and e.

Some of the results on the polymerization of racemic DBO are summarized in Table I. The agreement of the isotactic dyad percents, determined independently from the signal pairs b, c, and e, are satisfactory within the accuracy of the measurement. Obviously, the dyad tacticity of poly(DBO) depends markedly upon the polymerization temperature: It varied from 84% for the polymer obtained in methylene chloride at −90 °C to 48% for the polymer prepared in the same solvent at 0 °C. The effect of the solvents employed on the stereoregularity of the

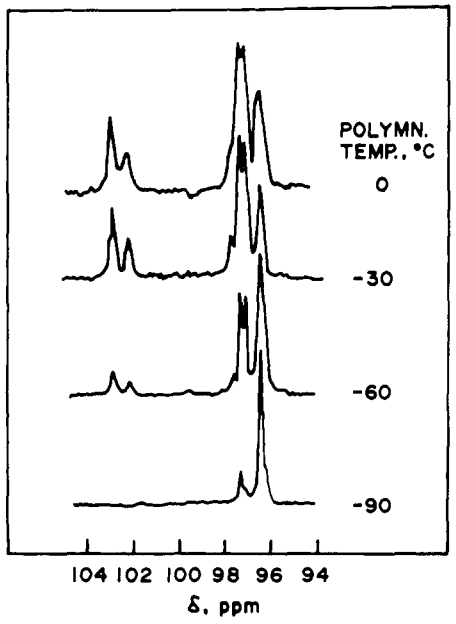


Figure 3. Polymerization temperature dependence of ^{13}C-NMR spectra of acetal carbon region of racemic poly(tetrahydropyran-2,6-diyloxymethylene) prepared in methylene chloride. Solvent, $CDCl_3$; concentration, 5–7%; 25 MHz; internal reference, tetramethylsilane.

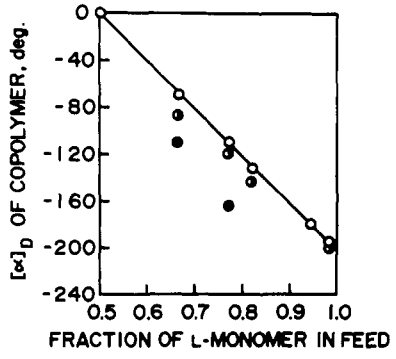


Figure 4. D,L copolymerization of optically active 6,8-dioxabicyclo[3.2.1]octane. Monomer, 0.56 g; solvent, CH_2Cl_2, 1.1 mL; initiator, BF_3·Et_2O, 2 mol %; temp, −78 °C. Conversion: ●, 10–15%; ◑, 65–80%; ○, 85–100%.

polymer seems to be insignificant. The temperature dependence of the "α-form" content determined by both ^1H- and ^{13}C-NMR spectroscopy was in good accord with that reported earlier.[2]

D,L Copolymerization of Optically Active Monomer Mixtures. The preferential formation of the isotactic dyad sequence along the polymer chain in the polymerization of DBO at lower temperatures as described in the foregoing section is strongly indicative of the stereoselection of the enantiomeric monomers by the growing chain control mechanism, because the stereoselection by the enantiomorphic catalyst sites control mechanism is very unlikely to take place with boron trifluoride etherate. In order to confirm this point, D,L copolymerization of monomer mixtures of different optical purities was undertaken in methylene chloride at −78 °C by using boron trifluoride etherate as the initiator.

The results are graphically shown in Figure 4. The straight line denotes the calculated specific rotation of D,L copolymers containing the same L contents as those in the starting mixtures. The fact that open circles which refer to the D,L copolymers obtained at 85–100% conversions are very close to or on this line implies that the specific rotation of D,L copolymer of DBO is determined solely by its composition. Half-filled circles (65–80% conversions) and filled circles (10–15% conversions) deviate appreciably downward from the straight line. This is a clear indication that the L enantiomer being in excess in the starting monomer mixture was preferentially incorporated into the D,L copolymer.

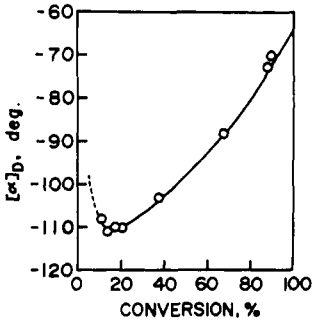
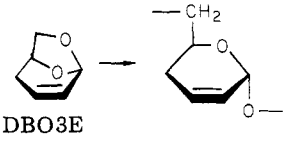


Figure 5. Specific rotation of D,L copolymers of 6,8-dioxabicyclo[3.2.1]octane as a function of conversion. Monomer, 0.56 g; L content in monomer, 66.5%; solvent, CH_2Cl_2, 1.1 mL; initiator, BF_3·Et_2O, 2 mol %; temp, −78 °C.

A variation in the specific rotation of the D,L copolymer with conversion is more distinctly illustrated in Figure 5. The specific rotation of the D,L copolymers starting from the monomer mixture of 66.5% L content reaches the minimum value ($[\alpha]_D$ −111°) at 13% conversion and increases up to the calculated value ($[\alpha]_D$ −65°) at 100% conversion. Such a remarkable conversion dependence of the specific rotation, that is, the composition of the products in the D,L copolymerization, provides a definitive support for the preferential selection of the monomer of the same chirality as that of the terminal unit of the growing chain.[12]

Possible Mechanism for Stereoregulation. The foregoing results and discussion lead us to the conclusion that the preferential formation of the isotactic dyad sequence along the polymer chain at low temperature arises from the stereoregulation displayed by the growing chain end. For speculating a possible mechanism for the steric control, the polymerization behavior of 6,8-dioxabicyclo[3.2.1]oct-3-ene (DBO3E) would be informative: The cationic polymerization of DBO3E initiated with boron trifluoride etherate does not yield, even at low temperature, a stereoregular polymer which is rich in isotactic dyad sequence, but instead a stereorandom polymer containing nearly equal amounts of isotactic and syndiotactic dyad sequences.[5]



DBO3E (2)

Molecular model inspection of DBO, DBO3E, and their growing chain ends reveals that a considerable steric strain arises when D monomer approaches the terminal L enantiomer unit of the growing chain or vice versa in the polymerization of DBO: As schematically illustrated in Figure 6 (upper half), there occurs steric repulsion between the equatorial hydrogen on the C(4) atom of the incoming D monomer and the equatorial hydrogen on the C(3) atom of the terminal L monomeric unit, even when the monomer approaches to the active center in such a way as to minimize steric repulsion. On the other hand, when L monomer approaches the terminal L monomeric unit, such steric repulsion can be avoided by taking a spatial arrangement which seems to be least sterically hindered

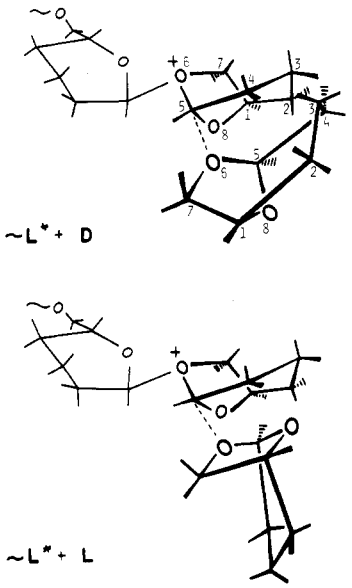


Figure 6. Possible polymerization scheme of 6,8-dioxabicyclo[3.2.1]octane.

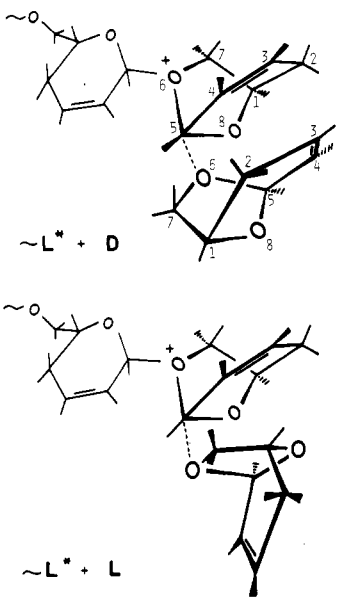


Figure 7. Possible polymerization scheme of 6,8-dioxabicyclo[3.2.1]oct-3-ene.

(Figure 6, lower half). Therfore, the propagation between the monomer and the terminal unit of the same chirality should occur more readily than the propagation between the monomer and the terminal unit of the opposite chirality, thus leading to a stereoregular polymer which is rich in isotactic dyad.

Polymerization of DBO3E is schematically represented in Figure 7. Even when D monomer approaches to the terminal L monomeric unit, the aforementioned unfavorable steric interaction between the hydrogen on the C(4) atom of the monomer and the hydrogen on the C(3) atom of the terminal unit almost disappears because of the nearly planar structures in the vicinity of the olefinic linkage between the C(3) and C(4) atoms (Figure 7, upper half). Consequently, the steric requirement for the propagation between the monomer and the terminal unit of the opposite chirality would not differ significantly from that for the propagation between the monomer and the terminal unit of the same chirality (Figure 7, lower half). Therefore, the stereoselection of the enantiomeric monomers by the growing chain end does not operate or, if any, becomes negligible in the polymerization of DBO3E, and only a stereorandom polymer is inevitably formed.

Stereospecific ring-opening polymerization of cyclic monomers by the growing chain control mechanism ordinarily requires coordination of monomer and growing chain to counterion[14-18] or helix formation.[19-21] In cationic polymerization of cyclic monomers, however, such coordination to counteranion seems very unlikely because of the nucleophilic character of the monomers, and hence, stereospecific polymerization would be extremely difficult. The formation of the stereoregular poly(DBO) which is rich in isotactic dyad, as described above, conceivably arises from the bulky, rigid bicyclic structure of the monomer possessing the two asymmetric centers in its molecule, and from the asymmetric environment created by its growing chain end, presumably involving the penultimate and even more remote units, toward the approach of the enantiomeric monomers. The observed depression in the stereoregularity of the polymers with the rise in the polymerization temperature is ascribable to the relatively small free-energy difference between the propagations of $\sim D^+ + D$ (or $\sim L^+ + L$) and $\sim D^+ + L$ (or $\sim L^+ + D$), and furthermore to the participation of an oxycarbenium ion in the propagation at higher temperature as reflected in the decrease in the α-form content of the polymers (Table I).[2]

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