Preparation and Characterization of Inclusion Complexes of Poly(propylene glycol) with Cyclodextrins

Akira Harada,* Miyuko Okada, Jun Li, and Mikiharu Kamachi*

Department of Macromolecular Science, Faculty of Science, Osaka University, Toyonaka, Osaka 560, Japan

Received May 22, 1995; Revised Manuscript Received September 5, 1995[⊗]

ABSTRACT: β-Cyclodextrin (β-CD) and γ-cyclodextrin (γ-CD) form inclusion complexes with poly(propylene glycol)s (PPG) of various molecular weights to give stoichiometric compounds in crystalline states. α-Cyclodextrin (α-CD) did not form complexes with PPG of any molecular weight. β- and γ-CD did not form complexes with the low molecular weight analogs, such as propylene glycol, di(propylene glycol), and tri(propylene glycol). The yields of the complexes of β- and γ-CD with PPG increased with increasing molecular weight (MW) of the PPG and reached a maximum at about MW 1000; yield decreased with a further increase in the MW. They were isolated and found to be 2:1 (monomer unit:CD). The complexes were characterized by IR, ^{1}H NMR, ^{13}C NMR, ^{13}C CP/MAS NMR, and ^{13}C PST/MAS NMR spectra and X-ray (powder), thermal, and elemental analyses. Complex formation of CDs with PPG derivatives has also been studied. The structures of the complexes are discussed. Complex formation of β-CD with atactic and isotactic PPG has been compared.

Introduction

Cyclodextrins (CDs) are a series of cyclic oligosaccharides consisting of 6−8 glucose units connected by α-1,4 linkages. They are called α-, β-, and γ-CD, respectively. They form inclusion complexes with a variety of low molecular weight compounds.[1] Recently, the design and synthesis of supramolecular structures by macromolecular recognition have attracted much attention. Previously we have reported that α-cyclodextrin (α-CD) formed complexes with poly(ethylene glycol)s (PEG) of various molecular weights to give crystalline compounds in high yields,[2] although β-CD did not form complexes with PEG of any molecular weight. However, we found that β-CD and γ-CD formed complexes with poly(propylene glycol) (PPG) to give crystalline complexes in high yields,[3] although α-CD did not form complexes with PPG of any molecular weight. The cross-sectional area of a polymer correlates with the size of the CD with which it forms a complex.[4] Moreover, we have prepared poly(rotaxane)s in which many α-CDs were threaded on a PEG chain.[5] Now we have studied the complex formation of β-CD and γ-CD with PPG in detail. The complex formation is chain-length-dependent and stoichiometric. This paper describes in detail the formation of inclusion complexes of cyclodextrins with PPG and its derivatives.

Results and Discussion

Selectivity of Complex Formation. Previously, we reported that α-CD formed complexes with poly(ethylene glycol)s of various molecular weights to give crystalline compounds, although β-CD did not form complexes with PEG. A poly(ethylene glycol) chain fits well into the cavity of α-CD. However, α-CD did not form complexes with poly(propylene glycol) (PPG) of any molecular weight. However, when PPG was added to saturated aqueous solutions of β-CD under sonication, the solution became turbid and the complexes were formed as crystalline precipitates.

Table 1 shows the complex formation of three hydrophilic polymers with cyclodextrins. PEG, which has the smallest cross-sectional area, selectively forms a complex with α-CD (diameter of the cavity = 4.5 Å) in high yield, while PPG, which has the larger cross-sectional area, selectively forms complexes with β-CD (diameter of the cavity = 7.0 Å) and γ-CD (diameter of the cavity = 8.5 Å) in high yield. It is of interest that poly(methyl vinyl ether), which has the same composition as PPG but carries a methoxy group as a side chain, does not form complexes with β-CD, but does form complexes with γ-CD.[6] These results indicate that the relative sizes of the cavities of cyclodextrins and the cross-sectional areas of the polymers are important in complex formation.

Table 1. Comparison of Hydrophilic Polymers with Various Chain Cross-Sectional Areas in the Formation of Crystalline Complexes with Cyclodextrins

		yield (%)		
polymer (MW)	structure	α-CD[a]	β-CD[b]	γ-CD[c]
PEG (1000)	$-(CH_2CH_2O)_n-$	92	0	trace
PPG (1000)	$-(CH_2CHO)_n-$ (CH$_3$)	0	96	80
PMVE (20000)	$-(CH_2CH)_n-$ (O–CH$_3$)	0	0	67

[a] α-CD-saturated aqueous solution, 1.5 mL; polymers, 15 mg. [b] β-CD-saturated aqueous solution, 7 mL; polymers, 15 mg. [c] γ-CD-saturated aqueous solution, 2 mL; polymers, 15 mg.

The selectivity in complex formation of polymers with cyclodextrins is higher than that of their complex formation with low molecular weight compounds. Since a polymer chain has many binding sites, each CD is able to recognize each binding site.

Effects of the Molecular Weight of PPG on Complex Formation. Figure 1 shows the results of complex formation of β-CD with PPG of various molecular weights. β-CD did not form complexes with the low molecular weight analogs, such as propylene glycol, di(propylene glycol), and tri(propylene glycol). β-CD formed complexes with PPG of molecular weight higher than 400. Yields of the complexes increase with increasing molecular weight. The complexes were obtained almost quantitatively between β-CD and PPG

[⊗] Abstract published in *Advance ACS Abstracts,* November 1, 1995.

0024-9297/95/2228-8406$09.00/0

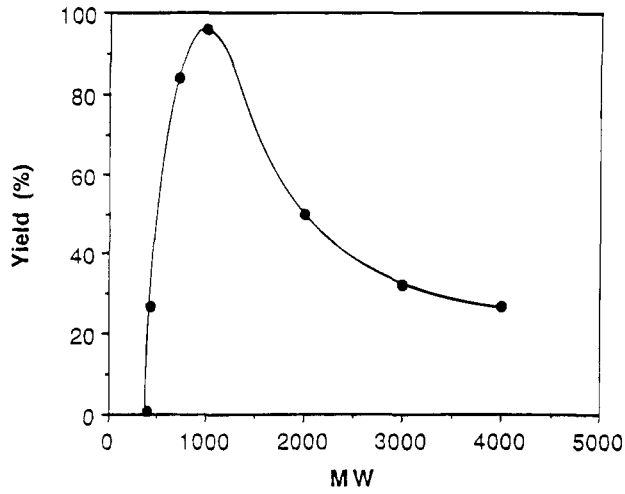


Figure 1. Yields of the complexes of β-CD with PPG as a function of the molecular weight of PPG. A saturated aqueous solution of β-CD (5 mL) was added at room temperature to tubes containing 20 mg of PPG. The mixture was agitated ultrasonically for 10 min and then allowed to stand overnight.

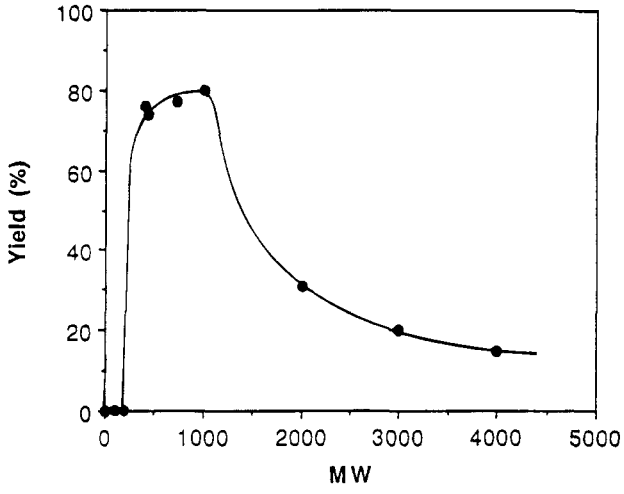


Figure 2. Yields of the complexes of γ-CD with PPG as a function of the molecular weight of PPG.

with a molecular weight of 1000, but for higher weight PPG the yields decrease with increasing molecular weight. This behavior is different from complex formation between α-CD and PEG, where the yields increase with increasing molecular weight and reach saturation. This may be due to the fact that PPG is more hydrophobic than PEG owing to the methyl group of the main chain. γ-CD also formed complexes with PPG, even with PPG of low molecular weight (MW = 400), in good yield (Figure 2), although β-CD gave low yields with PPG of low molecular weight (Figure 1). γ-CD did not form complexes with the low molecular weight analogs, such as propylene glycol, di(propylene glycol), and tri(propylene glycol). α-CD did not form complexes with PPG of any molecular weight, although it formed complexes with poly(ethylene glycol)s of various molecular weights to give crystalline complexes in high yields. By contrast, β-CD did not form complexes with PEG of any molecular weight. An α-CD cavity is too small for PPG to penetrate due to steric hindrance by methyl groups on the main chain.

Figures 1 and 2 show that a minimum chain length of PPG is required for the formation of crystalline complexes with β-CD and γ-CD. The same phenomenon was observed in the formation of crystalline complexes of PEG with α-CD. This is thought to be characteristic

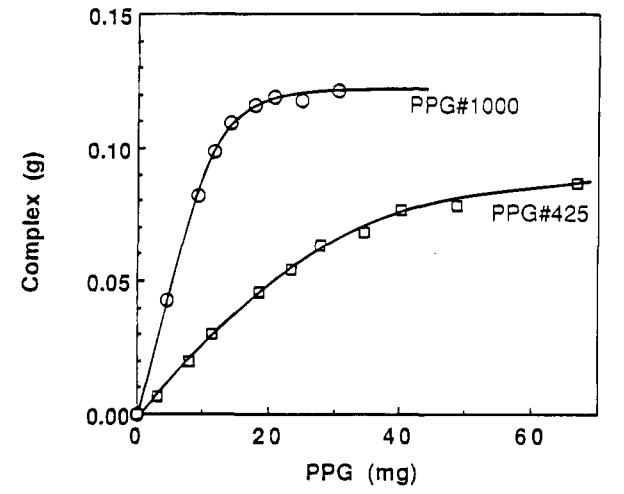


Figure 3. Yields of β-CD–PPG complexes as a function of added PPG with molecular weights of 425 (a) and 1000 (b). Seven milliliters of saturated aqueous solutions of β-CD was used.

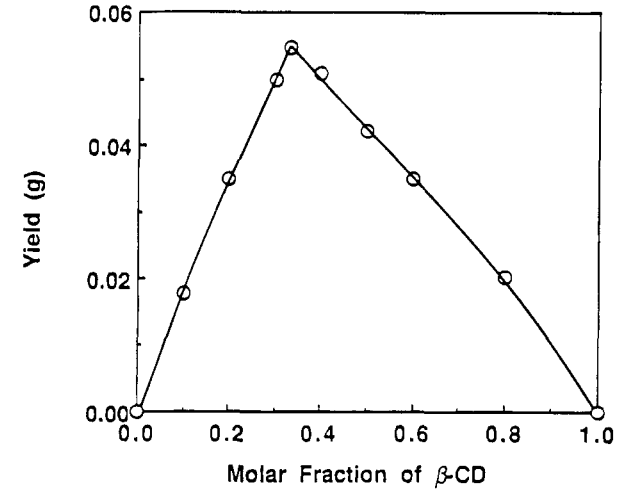


Figure 4. Continuous variation plot for complex formation between β-CD and PPG (MW = 1000). The sum of the initial concentrations of β-CD and PPG was fixed at 1.13×10^{-3} M.

of crystalline complex formation between hydrophilic polymers and cyclodextrins, reflecting the importance of cooperative effects in complex formation. The cooperation is thought to result from the fact that a single polymer chain has many binding sites that include cyclodextrin molecules. The neighboring cyclodextrin molecules bound on a polymer chain interact with each other by forming hydrogen bonds. This view is consistent with the fact that PPG does not form crystalline complexes with 2,6-di-*O*-methyl-β-CD, 2,3,6-tri-*O*-methyl-β-CD, and water-soluble β-CD–polymer. These compounds are thought to be unable to include a PPG chain to form crystalline complexes, because they cannot form hydrogen bonds due to the lack of hydroxyl groups.

Stoichiometry of the Complexes. Figure 3 shows plots of the yield of the complexes of PPG with β-CD obtained versus PPG added. This yield increased with an increase in the amount of PPG added to the aqueous solution of β-CD. It increased more slowly with PPG-425 than with PPG-1000. In Figure 3, saturation of the formation of the complexes, particularly with PPG-1000, was observed. The results indicate that the complex formation is stoichiometric. Figures 4 and 5 show continuous variation plots for the formation of complexes of PPG with β-CD and γ-CD. The two plots have

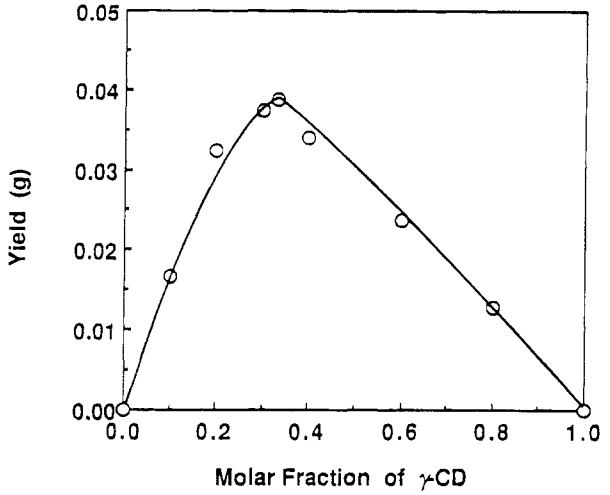


Figure 5. Continuous variation plot for complex formation between γ-CD and PPG (MW = 1000). The sum of the initial concentrations of γ-CD and PPG was fixed at 1.13×10^{-3} M.

maxima at a molar fraction of 0.33, suggesting that a CD interacts with two residues of the PPG chain.

The complexes were isolated by centrifugation and filtration, washed with water to remove uncomplexed CD, dried, and then washed with tetrahydrofuran to remove nonincluded PPG. Figure 6 shows the ^{1}H NMR spectrum of the complex between β-CD and PPG of molecular weight 1000. By comparing the integral of the peak of CD(1H) and that of the methyl group on PPG, two monomer units were found to bind to a β-CD molecule. It should be noted that the stoichiometries are always 2:1 (monomer unit:CD), regardless of the ratio of interesting CD and PPG. The methyl group of PPG at 1 ppm is broader in the presence of β-CD than in its absence, suggesting interactions between β-CD and the methyl group of PPG. We have also found that β-CD formed complexes with pluronic, the block copolymer of PEG–PPG–PEG. The stoichiometries are again 2:1 (PG unit:CD). These results are consistent with those recently reported by Topchieva et al.[7]

Properties. The complexes of β-CD with PPG of low molecular weight (MW = 400–700), which were isolated as crystalline complexes, are soluble in a large amount of water, but those with PPG of higher molecular weight are only sparingly soluble in water. This is in contrast to the complexes of PEG with α-CD, which are soluble in a large amount of water or by heating. This is due to the fact that PPG is more hydrophobic than PEG. The complexes are soluble in dimethyl sulfoxide and dimethylformamide. The X-ray diffraction studies (powder) show that all of the complexes are crystalline, in spite of the fact that PPG is a liquid.

DTA measurements of the complexes show that they decompose above 320 °C, i.e., at a temperature higher than that of nonincluded β-CD, which melts and decomposes below 310 °C, indicating that complexation with PPG stabilizes β-CD.

Binding Modes of the Complexes. Figure 7 shows the X-ray patterns of β-CD (a) and the complexes of β-CD with *p*-nitroacetanilide (b) and PPG (MW = 1000) (c). Saenger et al. reported that the structures of the inclusion complexes of CDs with low molecular weight compounds can be classified as "cage type" or "channel type".[8] The patterns show that all of the complexes are crystalline, and the pattern of the PPG complex is different from that of free β-CD and from those of the complexes with small molecules, such as propanol, but similar to that of the complex with *p*-nitroacetanilide, which has been proved to have a column structure by the X-ray study of a single crystal of the complex.[9] These results indicate that, in the PPG complex with β-CD, the CD exhibits packing different from that in free β-CD and has channel structures as in the complex with *p*-nitroacetanilide.

Figure 8a shows the CP/MAS NMR spectrum of the β-CD, and Figure 8b shows that of a complex of β-CD with PPG (MW = 1000). β-CD assumes a less symmetrical conformation in the crystal when it does not include a guest in the cavity. In this case, the spectrum shows resolved C-1 and C-4 resonances from each of the α-1,4-linked glucose residues. Two peaks at 94.3 and

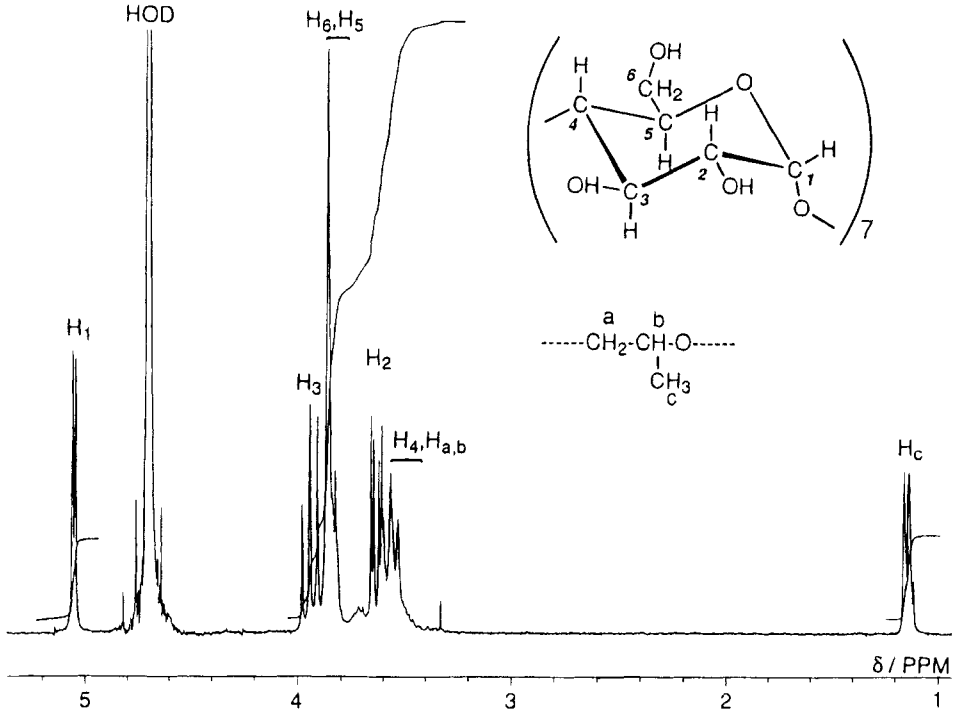


Figure 6. 270 MHz ^{1}H NMR spectrum of the complexes of PPG (MW = 1000) with β-CD in D_2O.

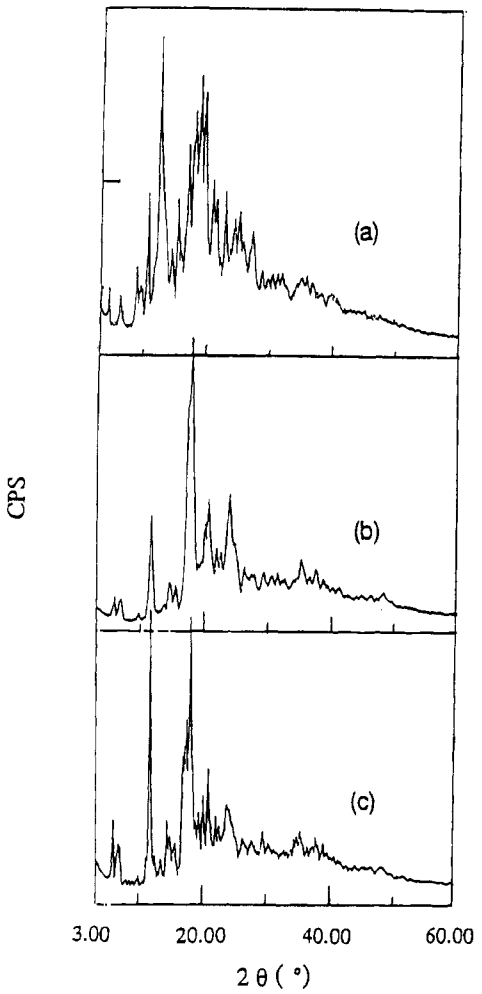


Figure 7. X-ray diffraction patterns for β-CD (a), β-CD–*p*-acetanilide complex (b), and β-CD–PPG (MW = 1000) complex (c).

96.8 ppm, which are assigned to the conformationally strained glycosidic linkage, are observed. On the other hand, in the spectrum of the β-CD–PPG complex, the peaks at 94.3 and 96.8 ppm disappeared. Each carbon of glucose can be observed in a single peak. These results indicate that β-CD adopts a symmetrical conformation and that each glucose unit of β-CD is in a similar environment. The X-ray studies of single crystals showed that β-CD adopts a symmetrical conformation when it includes a guest in the cavity.[9] CP/MAS NMR spectra of complexes and uncomplexed cyclodextrins are consistent with the results of X-ray studies. Therefore, a PPG chain is thought to be included in the cavities of cyclodextrins. Figure 8c shows the ^{13}C PST/MAS solid state NMR spectrum of the β-CD–PPG complex, which gives stronger signals of relatively flexible carbons of the sample than ^{13}C CP/MAS NMR. The intensities of the peaks of PPG relative to those of β-CD in Figure 8c are much stronger than those in Figure 8b, indicating that the PPG chain is not as rigid as β-CD in the complex. These results are consistent with the view that β-CD molecules are in the shape of a channel, forming the crystal frame of the complexes.

Molecular model studies show that PPG chains are able to penetrate β-CD cavities, while the PPG chain cannot penetrate α-CD cavities due to the hindrance of methyl groups on the main chain. Model studies further indicate that the single cavity accommodates two propylene glycol units. The inclusion complex formation of polymers with cyclodextrins is entropically unfavorable. However, formation of the complexes is thought to be promoted by hydrogen bond formation between cyclodextrins. Therefore, the head-to-head and tail-to-tail arrangement, which results in a more effective formation of hydrogen bonds between cyclodextrins, is thought to be the most probable structure. Such a structure was proved by X-ray studies on a single crystal of the complex between β-CD and *p*-nitroacetanilide. Figure 9 shows a proposed structure of the complex between β-CD and PPG.

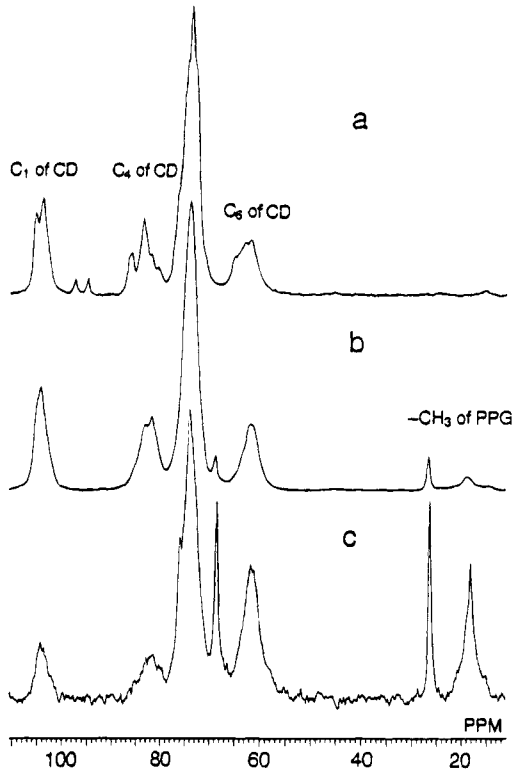


Figure 8. ^{13}C CP/MAS NMR spectra of β-CD (a) and the β-CD–PPG complex (b) and the ^{13}C PST/MAS NMR spectrum of the β-CD–PPG complex.

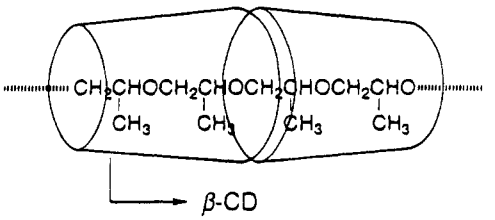
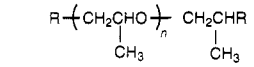


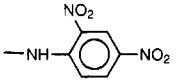
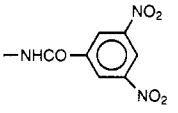
Figure 9. Proposed structure of the complex between β-CD and PPG.

Complex Formation of β-CD with Modified PPG. To study the effects of the end groups on complex formation, the yields of the complexes of β-CD with PPG with various end groups were studied. Table 2 shows the results of complex formation betwen β-CD and PPG with various end groups. PPG with small end groups such as hydroxy and amino groups formed complexes with β-CD in high yields. However, PPG having large substituents, such as 2,4-dinitrophenyl and 3,5-dinitrobenzoyl groups, did not form complexes with β-CD. These results indicate that PPG penetrates the cavities of cyclodextrins to form complexes with β-CD and γ-CD. The bulky end groups hindered the PPG chain from penetrating the cavities of cyclodextrins.

Complex Formation of β-CD with Isotactic PPG. To determine whether CDs recognize stereoregularity (tacticity) of polymers, we prepared isotactic PPG by

Table 2. Complex Formation between CD and PPG with Various End Groups



R	MW	yield (%) β-CD[a]	yield (%) γ-CD[b]
-OH	2000	50	31
$-NH_2$	2000	70	50
	2000	<1	12
	2000	<1	11

[a] Saturated β-CD solution, 5 mL; PPG, 20 mg; sonication for 10 min and allowed to stand for 1 h at room temperature. [b] 0.08g/mL γ-CD solution, 1 mL; PPG, 20 mg; sonication for 10 min and allowed to stand for 1 h at room temperature.

polymerization of propylene oxide using KOH as catalyst. *iso*-PPG was found to form complexes with β-CD in high yields, although it did not form complexes with α-CD. *iso*-PPG gave complexes with β-CD in lower yields (65% for MW = 1200) than did *atac*-PPG of similar average molecular weight (96% for MW = 1000). According to molecular modeling, *iso*-PPG is bulkier than *atac*-PPG, impeding movement into β-CD cavities.

Experimental Section

Materials. β-Cyclodextrin and γ-cyclodextrin were obtained from Nakarai Tesque Inc. and used after drying at 80 °C under vacuum with P_2O_5. 2,6-Di-*O*-methyl-β-cyclodextrin and 2,3,6-tri-*O*-methyl-β-cyclodextrin were obtained from Tousin Chemical Ltd. Propylene glycol, di(propylene glycol), and tri(propylene glycol) were purchased from Nakarai Tesque Inc. PPG of an average molecular weight of 400 (MW = 400) was purchased from Ishidzu Chemical, and those of MW 425 and 725 were from Aldrich. PPG of MW = 1000, 2000, 4000 were obtained from Wako Pure Chemical Ltd. The average molecular weight of the various polymer samples was found by GPC to be within the specification given by the suppliers. 2,4-Dinitro-1-fluorobenzene (DNFB) was obtained from Nakarai Tesque Inc. 3,5-Dinitrobenzoyl chloride and pyridine were obtained from Tokyo Kasei Inc. Water-soluble β-CD–polymer was prepared by the reaction of β-CD with epichlorohydrin.[10] Dimethylformamide (DMF) (Nakarai Tesque Inc.) was purified with reduced-pressure distillation from molecular sieves (4A) under a nitrogen atmosphere. Tetrahydrofuran (THF) (Nakarai Tesque Inc.) was fractionally distilled from CaH_2 under a nitrogen atmosphere. DMSO-d_6, $CDCl_3$, and D_2O, used as solvents in the NMR measurements, were obtained from Aldrich.

Preparation of Modified PPG. PPG–bis(2,4-dinitrophenylamine) was prepared by treatment of PPG–bisamine (MW = 2000) with 2,4-dinitro-1-fluorobenzene in DMF in a manner similar to that in the report[11] (yield, 80%). GPC analysis showed that the product had the same elution time and molecular weight distribution (M_w/M_n = 1.08) as those of the PPG-2000 product, and the product showed absorption at 360 nm, which indicated that the polymer was attached with the 2,4-dinitrophenylamine group. ^{1}H NMR (270 MHz, DMSO-d_6): δ_H 8.86 (2H, d, meta *H* of phenyl), 8.26 (2H, m, *H* of NH), 7.44 (2H, d, meta *H* of phenyl), 7.27 (2H, d, ortho *H* of phenyl), 4.04 (4H, d, *H* of CH_2N=), 3.51 (3H × 34, m, PPG), 1.03–1.25 (3H × 34, *CH*$_3$ of PPG).

PEG–bis(3,5-dinitrobenzamide) was prepared by the reaction of PPG–bisamine (MW 2000) with 3,5–dinitrobenzoyl chloride as described previously[12] (yield, 71%). GPC analysis showed that the product had the same elution time and molecular weight distribution (M_w/M_n = 1.08) as those of the PPG-2000 product, and the product showed absorption, indicating that 3,5-dinitrobenzamide groups were attached to the polymer. ^{1}H NMR (270 MHz, $CDCl_3$): δ_H 9.22 (2H, t, para *H* of phenyl), 9.17 (4H, d, ortho *H* of phenyl), 4.61 (4H, t, *H* of $CONHCH_2$), 3.63–3.89 (3H × 34, m, PPG), 1.05–1.24 (3H × 34, *CH*$_3$ of PPG).

Preparation of the Inclusion Complexes of Poly(propylene glycol)s with β-CD. Poly(propylene glycol)s or modified poly(propylene glycol)s (20.0 mg) were put into tubes. A saturated aqueous solution of β-CD (5.00 mL) containing 92.5 mg of β-CD was added at room temperature, and the mixtures were ultrasonically agitated for 10 min and then allowed to stand overnight at room temperature. The precipitated products were collected by centrifugation, dried under vacuum up to 100 °C, washed with THF, and then dried under vacuum up to 100 °C to give the β-CD–*atac*-PPG complexes.

***β*-CD–*atac*-PPG-425.** Yield: 27%. ^{1}H NMR (D_2O, 270 MHz): δ 5.05 (d, 7H, C(1)H of β-CD), 3.94 (t, 7H, C(3)H of β-CD), 3.86 (m, 14H, C(5)H and C(6)H or β-CD), 3.63 (m, 7H, C(2)H of β-CD), 3.56 (t, 7H, C(4)H of β-CD), 1.14 (m, 6H, methyl H of *atac*-PPG). ^{13}C NMR (DMSO-d_6, 67.9 MHz): δ 102.09 (C(1) of β-CD), 81.71 (C(4) of β-CD), 74.65 (methine C of *atac*-PPG), 73.19 (C(2) of β-CD), 72.58 (C(3) of β-CD), 72.19 (C(5) of β-CD), 60.08 (C(6) of β-CD), 17.44 (methyl C of *atac*-PPG). IR (KBr, cm^{-1}): 3381 (vs, ν_{OH}), 2926 (s, ν_{CH}), 1157, 1080, 1030 (vs, ν_{CO}). Anal. Calcd for $C_{48}H_{82}O_{37}\cdot 5.2H_2O$: C, 42.87; H, 6.93. Found: C, 42.58; H, 6.94.

***β*-CD–*atac*-PPG-725.** Yield: 84%. ^{1}H NMR (D_2O, 270 MHz): δ 5.05 (d, 7H, C(1)H of β-CD), 3.95 (t, 7H, C(3)H of β-CD), 3.86 (m, 14H, C(5)H and C(6)H of β-CD), 3.63 (m, 7H, C(2)H of β-CD), 3.57 (t, 7H, C(4)H of β-CD), 1.15 (m, 6H, methyl H of *atac*-PPG). ^{13}C NMR (DMSO-d_6, 67.9 MHz): δ 102.09 (C(1) of β-CD), 81.71 (C(4) of β-CD), 74.72 (methine C of *atac*-PPG), 73.20 (C(2) of β-CD), 72.57 (C(3) of β-CD), 72.19 (C(5) of β-CD), 60.08 (C(6) of β-CD), 17.40 (methyl C of *atac*-PPG). IR (KBr, cm^{-1}): 3365 (vs, ν_{OH}), 2926 (s, ν_{CH}), 1158, 1081, 1031 (vs, ν_{CO}). Anal. Calcd for $C_{48}H_{82}O_{37}\cdot 5.2H_2O$: C, 42.87; H, 6.93. Found: C, 42.83; H, 6.93.

***β*-CD–*atac*-PPG-1000.** Yield: 96%. ^{1}H NMR (D_2O, 270 MHz): δ 5.05 (d, 7H, C(1)H of β-CD), 3.94 (t, 7H, C(3)H of β-CD), 3.86 (m, 14H, C(5)H and C(6)H of β-CD), 3.63 (m, 7H, C(2)H of β-CD), 3.56 (t, 7H, C(4)H of β-CD), 1.14 (m, 6H, methyl H of *atac*-PPG). ^{13}C NMR (DMSO-d_6, 67.9 MHz): δ 102.11 (C(1) of β-CD), 81.71 (C(4) of β-CD), 74.74 (methine C of *atac*-PPG), 73.19 (C(2) of β-CD), 72.58 (C(3) of β-CD), 72.19 (C(5) of β-CD), 60.08 (C(6) of β-CD), 17.42 (methyl C of *atac*-PPG). IR (KBr, cm^{-1}): 3387 (vs, ν_{OH}), 2926 (s, ν_{CH}), 1158, 1081, 1031 (vs, ν_{CO}). Anal. Calcd for $C_{48}H_{82}O_{37}\cdot 5.2H_2O$: C, 42.87; H, 6.93. Found: C, 42.78; H, 6.99.

***β*-CD–*atac*-PPG-2000.** Yield: 50%. ^{1}H NMR (D_2O, 270 MHz): δ 5.05 (d, 7H, C(1)H of β-CD), 3.94 (t, 7H, C(3)H of β-CD), 3.86 (m, 14H, C(5)H and C(6)H of β-CD), 3.63 (m, 7H, C(2)H of β-CD), 3.56 (t, 7H, C(4)H of β-CD), 1.14 (m, 6H, methyl H of *atac*-PPG). ^{13}C NMR (DMSO-d_6, 67.9 MHz): δ 102.11 (C(1) of β-CD), 81.73 (C(4) of β-CD), 74.76 (methine C of *atac*-PPG), 73.21 (C(2) of β-CD), 72.58 (C(3) of β-CD), 72.21 (C(5) of β-CD), 60.10 (C(6) of β-CD), 17.42 (methyl C of *atac*-PPG). IR (KBr, cm^{-1}): 3381 (vs, ν_{OH}), 2925 (s, ν_{CH}), 1158, 1081, 1031 (vs, ν_{CO}). Anal. Calcd for $C_{48}H_{82}O_{37}\cdot 5.2H_2O$: C, 42.87; H, 6.93. Found: C, 43.26; H, 7.00.

***β*-CD–*atac*-PPG-4000.** Yield: 27%. ^{1}H NMR (D_2O, 270 MHz): δ 5.05 (d, 7H, C(1)H of β-CD), 3.95 (t, 7H, C(3)H of β-CD), 3.86 (m, 14H, C(5)H and C(6)H of β-CD), 3.63 (m, 7H, C(2)H of β-CD), 3.56 (t, 7H, C(4)H of β-CD), 1.14 (m, 12H, methyl H of *atac*-PPG). ^{13}C NMR (DMSO-d_6, 67.9 MHz): δ 102.16 (C(1) of β-CD) 81.77 (C(4) of β-CD), 74.79 (methine C of *atac*-PPG), 73.27 (C(2) of β-CD), 72.64 (C(3) of β-CD), 72.26 (C(5) of β-CD), 60.15 (C(6) of β-CD), 17.47 (methyl C of *atac*-PPG). IR (KBr, cm^{-1}): 3394 (vs, ν_{OH}), 2972, 2896, (s, ν_{CH}), 1156, 1083, 1030, (vs, ν_{CO}). Anal. Calcd for $C_{48}H_{82}O_{37}\cdot 5.2H_2O$: C, 42.87; H, 6.93. Found: C, 51.91; H, 8.64.

***β*-CD–*iso*-PPG(*R*).** Yield: 65%. ^{1}H NMR (D_2O, 270 MHz): δ 5.05 (d, 7H, C(1)H of β-CD), 3.94 (t, 7H, C(3)H of β-CD), 3.86 (m, 14H, C(5)H and C(6)H of β-CD), 3.63 (m, 7H, C(2)H of β-CD), 3.56 (t, 7H, C(4)H of β-CD), 1.14 (m, 12H, methyl H of *iso*-PPG). ^{13}C NMR (DMSO-d_6, 67.9 MHz): δ 102.11 (C(1) of β-CD), 81.73 (C(4) of β-CD), 74.83 (methine C

of *atac*-PPG), 73.58 (C(2) of β-CD), 72.58 (C(3) of β-CD), 72.21 (C(5) of β-CD), 60.10 (C(6) of β-CD), 17.42 (methyl C of *iso*-PPG). IR (KBr, cm^{-1}): 3371 (vs, ν_{OH}), 2916 (s, ν_{CH}), 1157, 1080, 1030 (vs, ν_{CO}). Anal. Calcd for $C_{52}H_{90}O_{38}\cdot 2.6H_2O$: C, 45.60; H, 7.0. Found: C, 45.42; H, 7.53.

β-CD–*iso*-PPG(*S*). Yield: 24%. ^1H NMR (D_2O, 270 MHz): δ 5.05 (d, 7H, C(1)H of β-CD), 3.94 (t, 7H, C(3)H of β-CD), 3.86 (m, 14H, C(5)H and C(6)H of β-CD), 3.63 (m, 7H, C(2)H of β-CD), 3,56 (t, 7H, C(4)H of β-CD), 1.14 (m, 8H, methyl H of *iso*-PPG). ^{13}C NMR (DMSO-d_6, 67.9 MHz): δ 102.09 (C(1) of β-CD), 81.71 (C(4) of β-CD), 74.81 (methine C of *atac*-PPG), 73.19 (C(2) of β-CD), 72.57 (C(3) of β-CD), 72.19 (C(5) of β-CD), 60.08 (C(6) of β-CD), 17.40 (methyl C of *iso*-PPG). IR (KBr, cm^{-1}): 3397 (vs, ν_{OH}), 2912 (s, ν_{CH}), 1155, 1080, 1030 (vs, ν_{CO}). Anal. Calcd for $C_{50}H_{86}O_{38}\cdot 0.5H_2O$: C, 46.12; H, 6.7. Found: C, 46.62; H, 7.2.

Isotactic PPGs were prepared from (*S*)-(−)-propylene oxide or (*R*)-(+)-propylene oxide (1.0 mL) with anhydrous KOH by a method similar to that previously reported.[13] The molecular weights of the polymers were estimated by GPC to be 1000–3000. The structures of the polymers were confirmed by ^1H and ^{13}C NMR spectra.

References and Notes

(1) (a) Bender, M. L.; Komiyama, M. *Cyclodextrin Chemistry;* Springer-Verlag: Berlin, 1978. (b) Szejtli, J. *Cyclodextrin and Their Inclusion Complexes;* Akademiai Kiado: Budapest, Hungary, 1982.

(2) (a) Harada, A.; Kamachi, M. *Macromolecules* **1990**, *23*, 2821. (b) Harada, A.; Li, J.; Kamachi, M. *Macromolecules* **1993**, *26*, 5698.

(3) Harada, A.; Kamachi, M. *J. Chem. Soc., Chem. Commun.* **1990**, 1322.

(4) Harada, A. *Polym. News* **1993**, *18*, 358.

(5) (a) Harada, A.; Li, J.; Kamachi, M. *Nature* **1992**, *356*, 325. (b) Harada, A.; Nakamitsu, T.; Li, J.; Kamachi, M. *J. Org. Chem.* **1993**, *58*, 7524. (c) Harada, A.; Li, J.; Kamachi, M. *J. Am. Chem. Soc.* **1994**, *116*, 3192. (d) Wenz, G.; Keller, B. *Angew. Chem., Int. Ed. Engl.* **1992**, *28*, 1103.

(6) Harada, A.; Li, J.; Kamachi, M. *Chem. Lett.* **1993**, 237.

(7) Topchieva, I. N.; Blyumenfel'd, A. L.; Klyamkin, A. A.; Polyakov, V. A.; Kabanov, V. A. *Polym. Sci.* **1994**, *36*, 221.

(8) (a) Sanger, W. *Jerusalem Symposium on Quantum Chemistry and Biochemistry*; Pullman, B. D., Ed.; Reidel Co.: Dordrecht, 1976. (b) McMullan, R. K.; Saenger, W.; Fayos, J.; Mootz, D. *Carbohydr. Res.* **1973**, *31*, 37.

(9) Harding, M. M.; MacLennan, J. M.; Paton, R. M. *Nature* **1978**, *274*, 621.

(10) Wiedenhof, N.; Lammers, J. N. J. J.; van Panthaleon, C. L.; van Eck, B. *Die Starke* **1969**, *21*, 119.

(11) Flanagan, D. D.; Barondes, S. H. *J. Biol. Chem.* **1975**, *250*, 1484.

(12) Suzuki, Y.; Tuchiya, N. *Bunsekikagaku* **1981**, *30*, 240.

(13) (a) Price, C. C.; Osgan, M.; Hughes, R. E.; Shambelan, C. *J. Am. Chem. Soc.* **1956**, *78*, 690. (b) St-Pierr, L. E.; Price, C. C. *J. Am. Chem. Soc.* **1956**, *78*, 3432. (c) Price, C. C.; Osgan, M. *J. Am. Chem. Soc.* **1956**, *78*, 4787.

MA9506952