Pergamon

Tetrahedron 58 (2002) 8237–8246

TETRAHEDRON

Highly stereoselective synthesis of chiral aldol polymers using repeated asymmetric Mukaiyama aldol reaction

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Received 2 May 2002; accepted 10 May 2002

Abstract—Asymmetric aldol polymerization of bis(triethylsilyl enol ether) and dialdehyde was performed in the presence of chiral *N*-sulfonyloxazaborolidinone as a catalyst. The polymerization occurred smoothly at low temperature (−78°C to −20°C) to afford optically active polymers having unique main-chain structure of β-hydroxy carbonyl repeating unit. In order to estimate the asymmetric induction during the polymerization, asymmetric aldol reaction of triethylsilyl enol ether and benzaldehyde was studied as a model reaction. Optical purity of the chiral polymers obtained from the asymmetric polymerization was determined by using ^{1}H NMR analysis after their chiral derivatization with (*R*)-*O*-acetylmandelic acid.

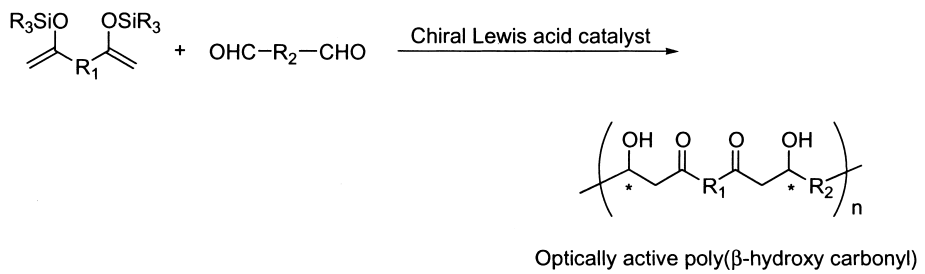
1. Introduction

Asymmetric synthesis polymerization is of much interest as an efficient method to produce optically active polymers from pro-chiral monomers.[1–3] Since tremendous progress has been made in the study of asymmetric reactions,[4,5] some of them can be successfully utilized as a polymerization reaction to synthesize chiral polymers. Particularly, asymmetric C–C bond forming reaction would be one of the possible candidates that can be applied to asymmetric polymerization. For example, we have found that asymmetric Diels–Alder reaction was repeated between bisdiene and bisdienophile to yield optically active polymers having main chain chirality.[6] We have also developed another example of asymmetric polymerization based on repeated Sakurai–Hosomi allylation reaction.[7–9] Recently we have found that asymmetric Mukaiyama aldol reaction can be used for the synthesis of chiral polymers having unique main chain structure.[10] Asymmetric aldol polymerization of dialdehyde and bis(silyl thioketene acetal) has been successfully demonstrated to yield optically active poly(β-hydroxy thioester)s.[10] In this paper we describe the asymmetric aldol polymerization of dialdehyde and bis(silyl enol ether) in the presence of chiral Lewis acid catalyst (Scheme 1). Optical purity of the obtained chiral poly(β-hydroxy carbonyl) was estimated based on the result of the corresponding model reaction. It is important to have more accurate information about the stereogenic centers induced in the polymer main chain. We have developed the method to determine the optical purity of the main chain chirality by ^{1}H NMR analysis of the chiral polymer after treatment with chiral derivatizing agent.

2. Results and discussion

2.1. Model reaction

Of chiral Lewis acid catalysts effective for Mukaiyama aldol reaction, chiral oxazaborolidinones are the most reliable and efficient catalyst.[11] In order to find a monomer structure suitable for asymmetric aldol polymerization we



Scheme 1. Asymmetric aldol polymerization of bis(silyl enol ether) and dialdehyde.

Keywords: Mukaiyama aldol reaction; asymmetric polymerization; chiral polymer; oxazaborolidinone; chiral derivatizing agent.

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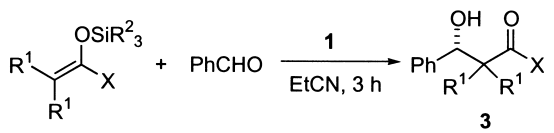
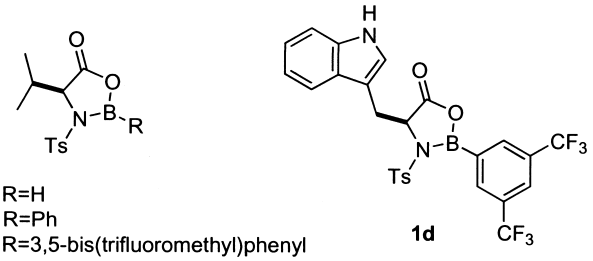
PII: S0040-4020(02)00973-0



2a: R^1=H, R^2=Me, X=SBu
2b: R^1=Me, R^2=Me, X=SEt
2c: R^1=H, R^2=Et, X=Ph

Scheme 2. Model reaction (1).

have tested enantioselective addition of several kinds of enolsilanes to benzaldehyde (Scheme 2) in the presence of chiral oxazaborolidinone catalyst **1** (Chart 1). Results of asymmetric aldol reaction are summarized in Table 1. Enantioselective addition of silyl thioketene acetal **2a** to benzaldehyde in the presence of **1a** afforded **3a** in high yield (90%) with enantioselectivity of 66% (Table 1, entry 1). *B*-Phenyl derivative (**1b**) of the oxazaborolidinone also catalyzed the same reaction to give **3a** in quantitative



1a: R=H
1b: R=Ph
1c: R=3,5-bis(trifluoromethyl)phenyl

Chart 1. Chiral oxazaborolidinone catalyst.

Table 1. Asymmetric Mukaiyama aldol reaction between enolsilane and benzaldehyde in the presence of chiral oxazaborolidinone catalyst

Entry	Catalyst	Temperature (°C)	Enolsilane	Product		
					Yield (%)	*R*/*S* (% ee)[a]
1	**1a**	−78	**2a**	**3a**	90	17.0:83.0 (66)
2	**1b**	−78	**2a**	**3a**	99	50:50 (0)
3[b]	**1b**	−78	**2b**	**3b**	87	62:38 (24)
4[c]	**1c**	−78	**2b**	**3b**	29	75:25 (50)
5	**1d**	−20	**2a**	**3a**	99	68.5:31.5 (37)
6	**1d**	−20	**2b**	**3b**	99	82.5:17.5 (65)
7	**1d**	−20	**2c**	**3c**	97	92:8 (84)
8	**1d**	−78	**2c**	**3c**	99	97:3 (93)

EtCN was used as a solvent unless otherwise stated.
[a] Determined by chiral HPLC (Chiralcel OD, hexane/2-propanol as an eluent).
[b] In CH_2Cl_2.
[c] 72 h in CH_2Cl_2.

Table 2. Asymmetric Mukaiyama aldol reaction between bis(triethylsilyl enol ether) **4** and benzaldehyde in the presence of chiral oxazaborolidinone catalyst **1d**

Entry	Temperature (°C)	Product			
			Yield (%)	(*R*,*R*)/(*R*,*S*)/(*S*,*S*)	*R*/*S* (% ee)[a]
1	−20	**8**	95	90.3:9.6:0.1	–
2	−78	**8**	97	95.9:4.0:0.1	–
3	−78	**8**	17	92.2:7.8:0.0	–
		9	74	–	97.0:3.0 (94)

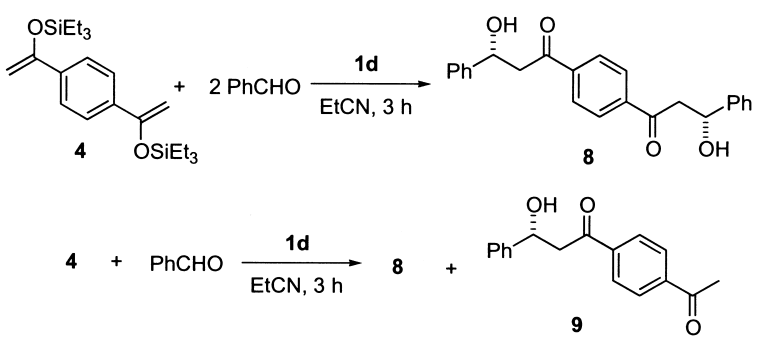
Reaction was performed in EtCN for 3 h in the presence of 20 mol% of **1d**.
[a] Determined by chiral HPLC (Chiralcel OD, hexane/2-propanol as an eluent).

conversion with no enantioselectivity (entry 2). The reaction with **2b** yielded the corresponding aldol **3b** with low enantioselectivity using this catalyst (entry 3). In the case of **1c** somewhat higher ee was obtained with lower yield of the aldol product (entry 4). Recently, Yamamoto reported that oxazaborolidinone **1d** prepared from *N*-(*p*-toluenesulfonyl)-(*S*)-tryptophan and 3,5-bis(trifluoromethyl)phenylboron dichloride was highly effective for the enantioselective addition of silyl enol ether to aldehyde.[12] We have tested this catalyst for the reaction between silyl thioketene acetals **2a** and **2b**. Unfortunately, low to moderate enantioselectivities were obtained for these substrates (entries 5 and 6). However in the case of the reaction with triethylsilyl enol ether **2c**, much higher enantioselectivity (84% ee) was achieved at −20°C with quantitative conversion (entry 7). The superior level of asymmetric induction (93% ee) was attained at −78°C (entry 8).

Another type of model reaction was performed between benzaldehyde and bis(triethylsilyl enol ether) **4** that is a monomer of asymmetric aldol polymerization (Scheme 3). In the presence of **1d**, 2 equiv. of benzaldehyde smoothly reacted with **4** in high yield with high stereoselectivity (Table 2, entries 1 and 2). The reaction of equimolecular quantities of benzaldehyde and **4** yielded a mixture of mono-adduct **9** (74%), bis-adduct **8** (17%) and 1,4-diacetylbenzene (9%) after hydrolytic workup.

2.2. Monomer synthesis

We have prepared dialdehydes and bis(silyl enol ether)s as monomers for asymmetric aldol polymerization. Chiral polymers can be synthesized by means of repeated asymmetric aldol reaction between these monomers. Dialdehydes **6** were prepared from *p*-hydroxybenzaldehyde



Scheme 3. Model reaction (2).

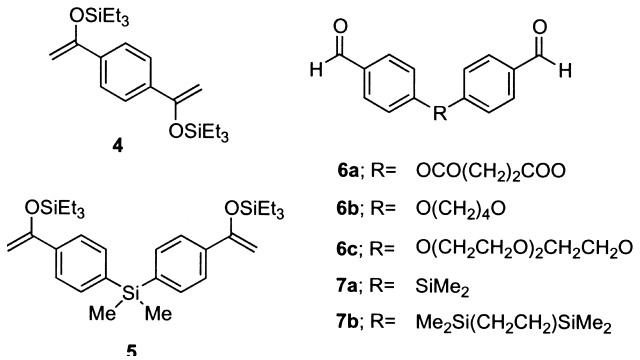
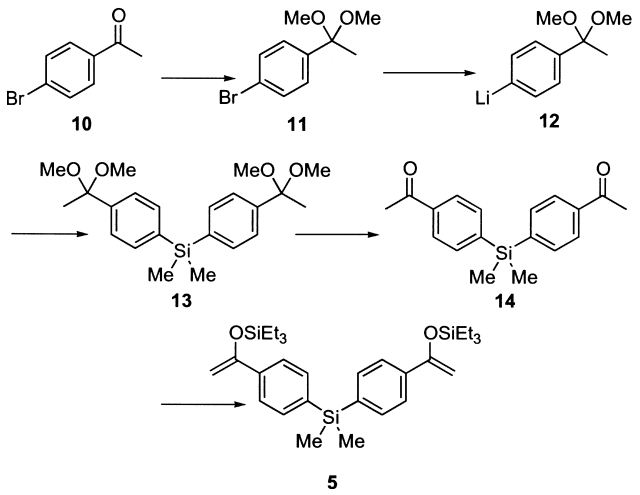


Chart 2. Monomers for asymmetric aldol polymerization.

according to the method reported in the previous paper.[8] Another dialdehydes **7** possessing silyl group were prepared from coupling of *p*-lithiated benzaldehyde dimethylacetal and chlorosilanes (Chart 2).[13] High purity of monomers is always required to obtain polymers by using polyaddition method. Bis(triethylsilyl enol ether) **4** was prepared with high purity from diacetylbenzene according to the method reported in the previous paper.[14] Although the corresponding trimethylsilyl enol ether was prepared by the same procedure, this monomer isolated by distillation was always contaminated with nearly 10% of the mono-desilylated compound. Several attempts to purify the bis(trimethylsilyl enol ether) monomer were unsuccessful. On the other hand, the remarkable ability of triethylsilyl group to stabilize silyl ethers and suppress their tendency to decompose has been well documented.[15] We have then prepared a new monomer **5** according to the procedure described in Scheme 4. Protected bromoacetophenone **11** was lithiated and coupled with 0.5 equiv. of dichlorodimethylsilane to form bisacetal **13**. Deprotection of the acetal followed by silyl enol ether formation gave bis(triethylsilyl enol ether) **5**. This monomer can be purified by usual silica gel chromatography and is stable enough to be stored under nitrogen at −20°C for at least several days.



Scheme 4. Preparation of monomer **7**.

2.3. Asymmetric polymerization

Model reactions mentioned earlier prompted us to perform asymmetric polymerization of bis(triethylsilyl enol ether) and dialdehyde using **1d** as a chiral catalyst. We have examined the polymerization of **4** and **6a** at −20°C to yield **15a** in 74% yield (Table 3, entry 1). The structure of polymer **15** was confirmed by NMR spectroscopy that shows a unique main chain structure of poly(β-hydroxy carbonyl), and may be difficult to prepare by other polymerization methods (Scheme 5). Lowering the amount of the catalyst decreased the yield and the molecular weight of the polymer (entries 2 and 3). Dilution of the initial monomer solution in propionitrile yielded the polymer having higher molecular weight (entry 4). Reactivity of dialdehydes containing ether linkages **6b** and **6c** is quite low to obtain polymer (entries 5 and 6). By using above monomers, almost no polymerization occurred below −20°C mainly because of low solubility of dialdehyde monomer **6** in propionitrile. On the other hand, introduction of silyl group into the monomer structure dramatically improved the solubility. A clear solution of silyl containing monomer **7** was obtained at −78°C. However the reaction

Table 3. Asymmetric aldol polymerization of bis(triethylsilyl enol ether) and dialdehyde in the presence of **1d**

Entry	Bis(silyl enol ether)	Dialdehyde	Product	Temperature (°C)	Chiral aldol polymer				
					Yield[a] (%)	M_w[b]	M_w/M_n[b]	$[\alpha]_D$[c]	$[\Phi]_{435}$[d]
1	**4**	**6a**	**15a**	−20	74	2500	4.36	+37	+219
2[e]	**4**	**6a**	**15a**	−20	47	1500	3.38	+93	+404
3[f]	**4**	**6a**	**15a**	−20	0	–	–	–	–
4[g]	**4**	**6a**	**15a**	−20	43	4500	1.71	+61	+367
5	**4**	**6b**	**15b**	−20	26	880	3.61	+52	+241
6	**4**	**6c**	**15c**	−20	0	–	–	–	–
7	**4**	**7a**	**16a**	−78 to −20	71	48200	10.3	+101	+1670
8	**4**	**7b**	**16b**	−78 to −20	98	22900	5.67	+76	+1021
9	**5**	**7a**	**17a**	−78 to −20	94	22500	4.44	+78	+1143
10	**5**	**6b**	**17b**	−78 to −20	90	13200	3.16	+61	+1058

Polymerization of bis(silyl enol ether) (1 mmol) and dialdehyde (1 mmol) was carried out in EtCN (6 mL) in the presence of 20 mol% of **1d** unless otherwise stated.

[a] Isolated yield of the polymer precipitated in MeOH/H_2O.

[b] Determined by GPC calibrated by linear polystyrene standards.

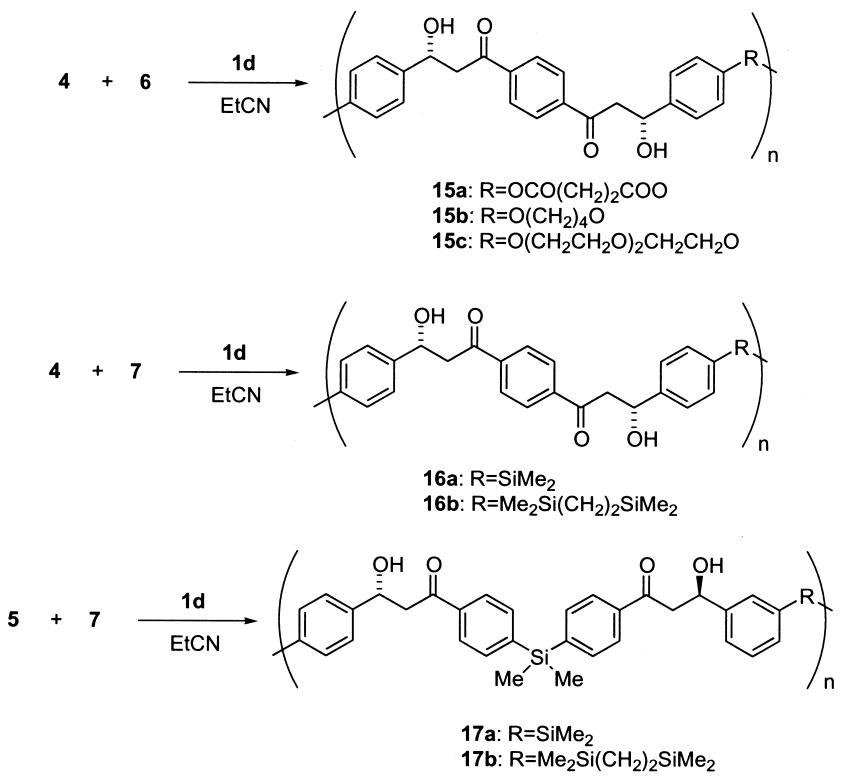
[c] Measured in THF (*c* 1.00).

[d] Molar optical rotation value defined as follows: $[\Phi]=[\alpha](M/100)$, where $[\alpha]$ is an optical rotation value and M is the weight of the repeating polymer unit.

[e] 10 mol% of the catalyst was used.

[f] 5 mol% of the catalyst was used.

[g] 10 mL of EtCN was used.

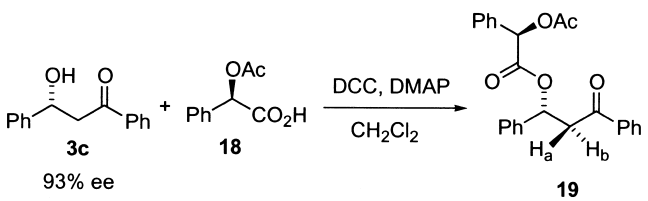


Scheme 5. Asymmetric aldol polymerization.

with bis(silyl enol ether) afforded only oligomers at this temperature, which were not precipitated in MeOH/H_2O (2:1). Thus we performed the asymmetric polymerization of these monomers at −78°C for 1 h and then allowed to warm to −20°C. Under this condition, chiral polymers that can be precipitated in MeOH/H_2O (2:1) were obtained in high yield with higher molecular weight (entries 7–10). These polymers are soluble in common organic solvents such as THF, CH_2Cl_2, $CHCl_3$, DMF, and DMSO. All the chiral polymers obtained using **1d** as a catalyst showed positive optical rotation value.

2.4. Determination of optical purity of the chiral polymer

Although the determination of optical purity of chiral polymers is definitely very important, many reports on the asymmetric polymerization have not dealt with this point mainly due to its difficulty.[1] Only a few papers examined to determine optical purity of chiral polymers synthesized by asymmetric polymerization.[16] Regarding our chiral polymers we can assume that highly stereoselective polymerization occurs in the asymmetric polymerization using **1d** as a chiral catalyst based on the results obtained from the model reactions. However it is important to



Scheme 6. *O*-Acetylmandelate of chiral aldol.

investigate the determination method of optical purity of chiral polymers. Chromatographic method that is widely used for various kinds of chiral compounds cannot be used to determine their optical purities. One of the possible methods may be to use NMR measurement of the chiral polymer treated with chiral derivatizing agent. This methodology has been well established for the low-molecular-weight chiral compounds.[17] First, we applied this method to the aldol adduct **3c**, which was treated with *O*-acetylmandelic acid as a chiral derivatizing agent to give **19** (Scheme 6) ^{1}H NMR analysis of **19** made it possible to determine the enantiopurity of **3c**. As shown in Fig. 1 NMR peaks of diastereomeric methylene protons were clearly separated after transformation to its *O*-acetylmandelate. We have then applied the same method to determine the optical purity of the chiral polymers.[18] Aldol polymerization of monomers **5** and **7** using $Sc(OTf)_3$ as achiral catalyst afforded an authentic polymer sample having the same NMR spectrum as that of **17a**. We have modified hydroxy groups of the authentic polymer with enantiopure (*R*)-*O*-acetylmandelic acid. After the chiral derivatization ^{1}H NMR spectra of the polymer showed clear separation in the corresponding methylene region (Fig. 2(A)). By using ^{1}H NMR data of the *O*-acetylmandelated polymer we determined the optical purity of the chiral polymers (Scheme 7). The corresponding optically active polymer **17a** was also treated with (*R*)-*O*-acetylmandelic acid to give **21a**. From NMR data shown in Fig. 2(B) *R*/*S* ratio of main chain stereogenic centers in **17a** was determined to be 97.0:3.0. The results of optical purity of the chiral polymers are summarized in Table 4. These results indicate that asymmetric aldol polymerization of bis(triethylsilyl enol ether) and dialdehyde using **1d** occurred in highly stereoselective manner to give optically active polymer.

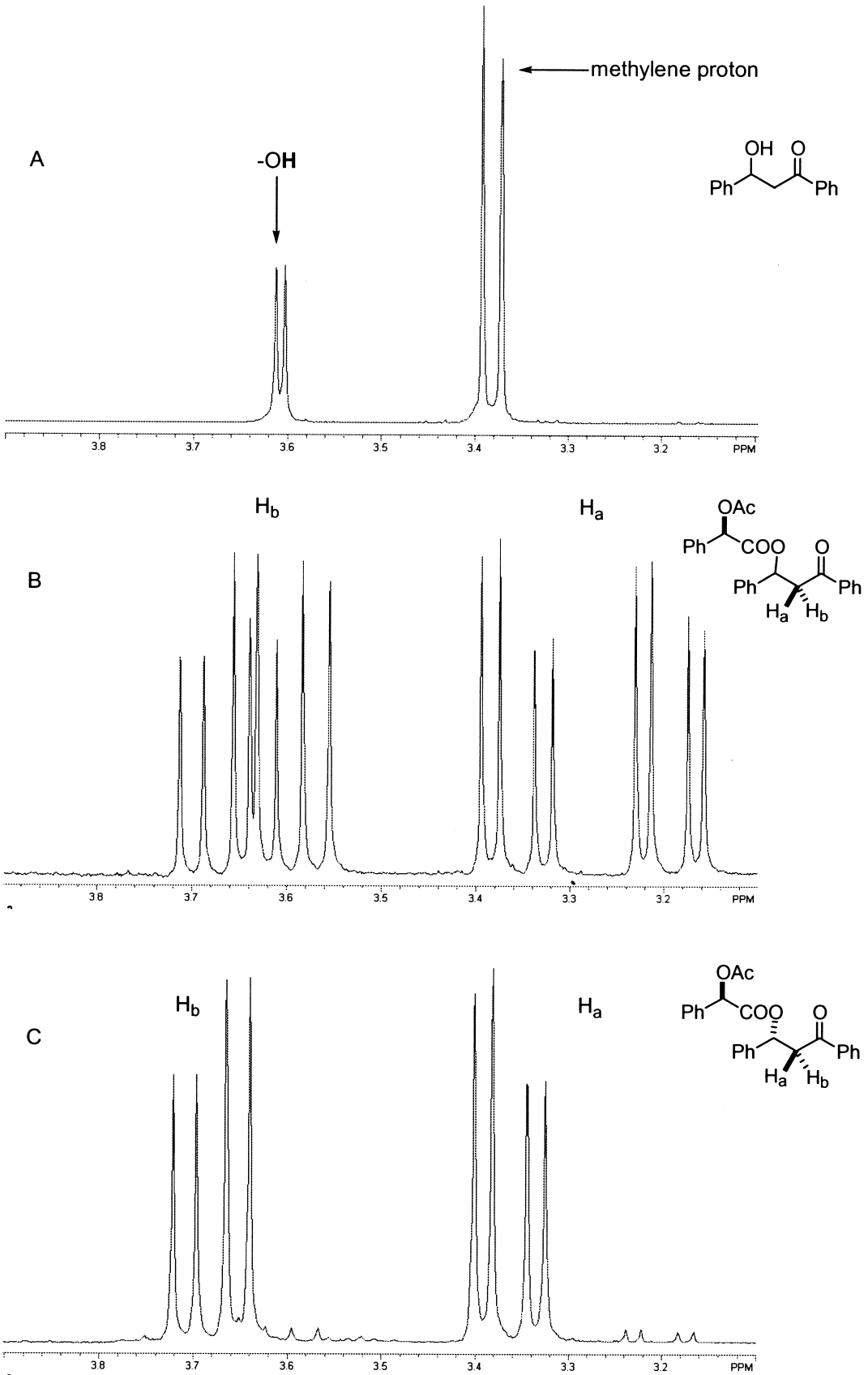


Figure 1. ^{1}H NMR spectra of methylene region of aldol adduct **3c** (A), racemic **19** (B), and **19** (C).

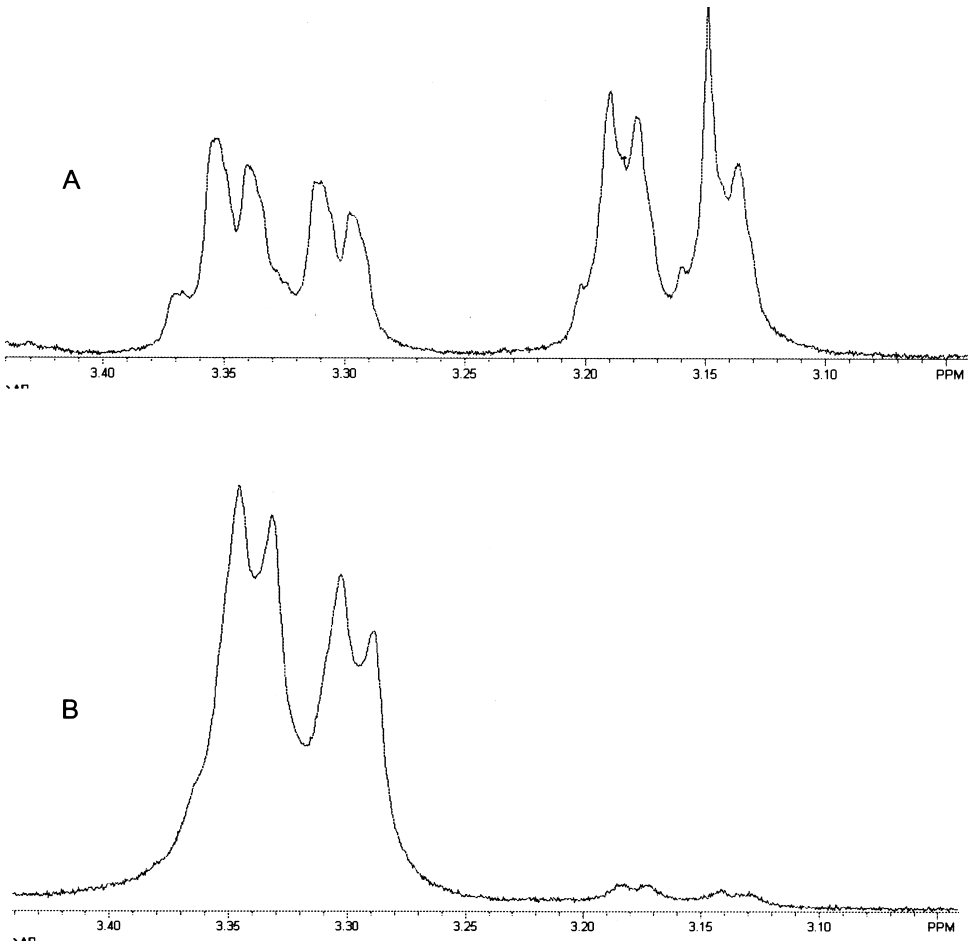
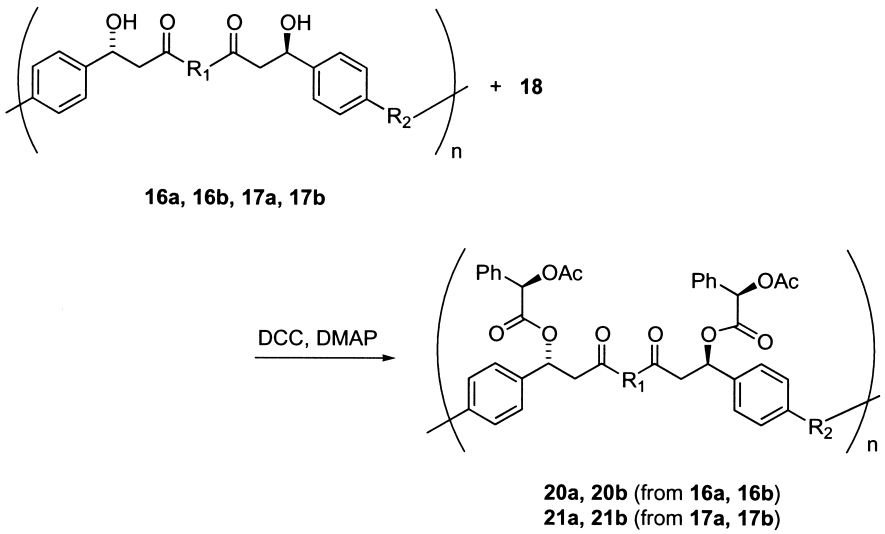


Figure 2. [1]H NMR spectrum of methylene region of the authentic polymer **21a** (A) and optically active polymer **21a** (B).



Scheme 7. Preparation of *O*-acetylmandelate of chiral aldol polymer.

Table 4. Optical purity of the chiral polymers determined by NMR analysis

Entry	Chiral polymer	Mandelate polymer	Optical purity (*R*/*S*)
1	**16a**	**20a**	97.5:2.5
2	**16b**	**20b**	96.5:3.5
3	**17a**	**21a**	97.0:3.0
4	**17b**	**21b**	97.5:2.5

3. Conclusions

Asymmetric Mukaiyama aldol reaction between triethylsilyl enol ether and aldehyde was found to proceed smoothly with high enantioselectivity in the presence of chiral oxazaborolidinone catalyst **1d**. We have prepared new monomers of bis(silyl enol ether)s and dialdehydes for the asymmetric aldol polymerization. Asymmetric

polymerization was performed using **1d** to give the chiral polymers having main chain configurational chirality. Optical purity of the chiral polymers can be roughly estimated based on the results of model reactions. We have determined the optical purity by means of ^{1}H NMR measurement of the *O*-acetylmandelated polymers. This is the first example of the asymmetric polyaddition with high level of optical induction. Direct determination method of optical purity of chiral polymer by NMR measurement may be useful and applicable to analyze various kinds of chiral polymers.

4. Experimental

4.1. General method and materials

All reactions were carried out under an atmosphere of dry nitrogen. Tetrahydrofuran (THF) was freshly distilled from sodium benzophenone ketyl under nitrogen immediately before use. Dichloromethane (CH_2Cl_2) and propionitrile were distilled from CaH_2. Reactions were monitored by TLC using Merck precoated silica-gel plates (Merck 5554, $60F_{254}$). Column chromatography was performed with a silica gel column (Wakogel C-200, 100–200 mesh).

4.2. Measurements

Melting points were determined on a Yanaco micromelting apparatus and were uncorrected. Optical rotations were measured on a JASCO DIP-140 digital polarimeter using a 10 cm thermostated microcell. Both ^{1}H (300 MHz) and ^{13}C (75 MHz) spectra were recorded on Varian Mercury 300 spectrometer using tetramethylsilane as an internal standard, and *J* values are reported in Hz. IR spectra were recorded with a JEOL JIR-7000 FT-IR spectrometer and were reported in reciprocal centimeter (cm^{-1}). Elemental analyses were performed by the Microanalytical Center of Kyoto University. HPLC analyses were performed with a JASCO HPLC system composed of 3-Line Degasser DG-980-50, HPLC pump PV-980, Column oven CO-965, equipped with a chiral column (Chiralcel OD, Chiralcel OD-H, Daicel) using hexane/propane-2-ol as an eluent. UV detector JASCO UV-975 was used for the peak detection. Size exclusion chromatography (SEC) for the characterization of molecular weight and its distribution was conducted at 40°C with JASCO PU-980 as a pump, JASCO UVDEC-100-III as a UV detector and Shodex column KF-806×2 as columns. The eluent was THF and flow rate was 1.0 mL/min. A molecular weight calibration curve was obtained by using a series of polystyrene standards (Tosoh Co., Japan).

4.3. Preparation of silyl enol ethers

Silyl enol ethers **2a** and **2b** were prepared according to the method reported in the literature.[19]

4.3.1. 1-Phenyl-1-(triethylsilyloxy)ethylene (2c). To a THF (25 mL) solution of lithium diisopropylamide (2.0 M in hexane, 12 mL, 24 mmol) was added a THF (10 mL) solution of acetophenone (2.86 g, 23.8 mmol) at −78°C. After stirring for 30 min at −78°C chlorotriethylsilane (4 mL, 24 mmol) was added slowly and then stirred for another 30 min. The reaction mixture was allowed to warm to room temperature and poured into water. The reaction mixture was then extracted with hexane and washed with brine. The organic layers were combined, dried over Na_2SO_4, and concentrated under reduced pressure. The residue was purified via a Kugelrohr distillation to afford compound **2c** (4.3 g, 78%). ^{1}H NMR ($CDCl_3$) 7.63 (d, *J*=7.8 Hz, 2H), 7.26–7.34 (m, 3H), 4.48 (s, 1H), 4.43 (s, 1H), 1.02 (t, *J*=7.8 Hz, 9H), 0.81 (q, *J*=7.8 Hz, 6H). ^{13}C NMR ($CDCl_3$) 156.0, 137.9, 128.4, 128.3, 125.4, 90.61, 6.97, 5.16. Anal. calcd for $C_{14}H_{22}OSi$: C, 71.73; H, 9.46. Found: C, 71.50; H, 9.51%.

4.3.2. 1,4-Bis[1-(triethylsiloxy)vinyl]benzene (4). To a solution of 1,4-diacetylbenzene (3.0 g, 19 mmol) and Et_3N (5.8 mL, 40 mmol) in acetonitrile (15 mL) was added chlorotriethylsilane (7.0 mL, 42 mmol) at room temperature. The reaction mixture was heated to 40°C and a propionitrile (35 mL) solution of NaI (6.5 g, 43 mmol) was added. After being stirred for 4 h at room temperature the whole mixture was poured into water and quickly extracted with hexane (2×100 mL). The organic layers were combined, washed with brine, dried over $NaSO_4$, and concentrated under reduced pressure. The crude residue was subjected to chromatography (hexane) to afford compound **4** (4.5 g, 60%) as colorless oil. IR (neat) 2955, 1237, 1072. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.57 (s, 4H), 4.89 (d, *J*=1.7 Hz, 2H), 4.42 (d, *J*=1.7 Hz, 2H), 1.01 (t, *J*=7.5 Hz, 18H), 0.77 (t, *J*=7.5 Hz, 12H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.8, 137.6, 125.1, 90.7, 7.00, 5.16. Anal. calcd for $C_{22}H_{38}O_2Si_2$: C, 67.63; H, 9.80. Found: C, 67.41; H, 9.85%.

4.3.3. Bis(4-acetylphenyl)dimethylsilane (14). 4-Bromoacetophenone dimethylacetal **11** (11.0 g, 47 mmol) was dissolved in dry THF (150 mL) under nitrogen. *n*-BuLi/hexane solution (1.6 M, 30 mL, 48 mmol) was added slowly at −78°C over 30 min. After being stirred for 4 h at −78°C, dichlorodimethylsilane (2.8 mL, 23 mmol) was added to the reaction mixture. The reaction mixture was then stirred for additional 1 h at −78°C, allowed to room temperature and was stirred for 10 h. The reaction mixture was quenched with 2N HCl and stirred for 2 h at room temperature. The reaction mixture was then concentrated under reduced pressure. The aqueous layer was then extracted with EtOAc (3×70 mL). Organic layers were combined, washed with brine, dried over Na_2SO_4 and concentrated under reduced pressure. The crude residue was purified by column chromatography (hexane/EtOAc, 2:1) to afford a yellow viscous oil (3.4 g, 50%). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.92 (d, *J*=8.5 Hz, 4H), 7.61 (d, *J*=8.5 Hz, 4H), 2.60 (s, 6H), 0.61 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 198.5, 144.2, 137.9, 134.6, 127.6, 26.9, −2.56. IR (neat) 3018, 1684, 1266, 813. Anal. calcd for $C_{18}H_{20}O_2Si_2$: C, 72.93; H, 6.80. Found: C, 72.78; H, 6.62%.

4.3.4. Bis[4-(1-triethylsiloxy)vinylphenyl]dimethylsilane (5). This compound (88%) was prepared from diketone **21** (2.96 g, 10 mmol), Et_3N (2.9 mL, 21 mmol), chlorotriethylsilane (3.7 mL, 22 mmol), NaI (3.4 g, 23 mmol) in acetonitrile (25 mL) according to the same procedure described earlier for obtaining compound **4** from 1,4-diacetylbenzene.

Compound **5**. ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.61 (d, J=8.5 Hz, 4H), 7.49 (d, J=8.5 Hz, 4H), 4.91 (d, J=1.7 Hz, 2H), 4.44 (d, J=1.7 Hz, 2H), 1.03 (d, J=8.2 Hz, 18H), 0.80 (q, J=8.2 Hz, 12H), 0.56 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.9, 138.3, 134.1, 124.6, 90.6, 6.71, 6.44, 4.98, −2.33. IR (neat) 2956, 1246, 1091, 1010, 742. Anal. calcd for $C_{30}H_{48}O_2Si_3$: C, 68.64; H, 9.22. Found: C, 68.04; H, 9.53%.

4.4. Model reaction

Asymmetric reactions of enolsilane and aldehyde were performed according to general methods reported by Yamamoto et al.[12]

4.4.1. Enantioselective addition of silyl thioketene acetal 2a to benzaldehyde. To a suspension of *N*-(*p*-toluenesulfonyl)-(*S*)-tryptophan[20] (43 mg, 0.12 mmol) in dichloromethane (0.5 mL) was added 3,5-bis(trifluoromethyl)-phenylboron dichloride (30 mg, 0.1 mmol) at room temperature. After being stirred for 1 h, the reaction mixture was concentrated in vacuo to give **1d** as a white solid. **1d** was then dissolved in propionitrile (1 mL) and cooled to −20°C. A solution of benzaldehyde (0.14 mL, 1.38 mmol) and thioketene silylacetal (224 mg, 1.1 mmol) in propionitrile (2 mL) was added to the above catalyst solution and stirred for 3 h at −20°C. The reaction mixture was poured into water and extracted with EtOAc (2×25 mL). The organic layers were combined, dried over Na_2SO_4 and evaporated. The residue was dissolved in THF (5 mL) and 2N HCl (1 mL) was added. After being stirred for 30 min at room temperature, the mixture was concentrated under reduced pressure. The aqueous phase was extracted with EtOAc (2×25 mL), washed with brine, dried over Na_2SO_4, and evaporated to an oily residue. Silica gel column chromatography (hexane/EtOAc, 5:1) afforded 245 mg (99% yield) of the aldol product **3a**.[10] The enantiomeric excess (37% ee) was determined by chiral HPLC analysis using Chiralcel OD-H column (hexane/2-propanol, 99:1), 0.5 mL/min, t_R=45.6 min (*S*), t_R=49.8 min (*R*).

4.4.2. Enantioselective addition of 2b to benzaldehyde. The procedure used for the preparation of **3a** from **2a** in the presence of chiral catalyst **1d** was identical to that for the preparation of **3b**.[21]

4.4.3. Enantioselective addition of 2c to benzaldehyde. Chiral catalyst **1d**, prepared from *N*-(*p*-toluenesulfonyl)-(*S*)-tryptophan (46 mg, 0.13 mmol) and 3,5-bis(trifluoromethyl)phenylboron dichloride (35 mg, 0.12 mmol) was dissolved in propionitrile (1 mL) and cooled to −78°C. A solution of benzaldehyde (0.10 mL, 0.984 mmol) and triethylsilylenol ether **2c** (256 mg, 1.09 mmol) was added to the catalyst solution and stirred for 3 h at −78°C. The reaction mixture was poured into water and extracted with EtOAc (2×25 mL). The organic layers were combined, dried over Na_2SO_4 and evaporated. The residue was dissolved in THF (5 mL) and 2N HCl (1 mL) was added. After being stirred for 2 h at room temperature, the mixture was concentrated under reduced pressure. The aqueous phase was extracted with EtOAc (2×25 mL), washed with brine, dried over Na_2SO_4, and evaporated to an oily residue. Silica gel column chromatography (hexane/EtOAc, 4:1) afforded 220 mg (99% yield) of the aldol product **3c**.[22] The enantiomeric excess (93.2% ee) was determined by chiral HPLC analysis using Chiralcel OD column (hexane/2-propanol, 20:1), 0.3 mL/min, column temperature; 30°C, t_R=57.1 min (*S*), t_R=65.5 min (*R*). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.98–7.26 (m, 10H), 5.35 (t, J=2.8 Hz, 1H), 3.61 (d, J=2.8 Hz, 1H), 3.38 (d, J=6.0 Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 200.5, 143.1, 136.8, 133.9, 129.0, 128.8, 128.4, 127.9, 126.0, 70.28, 47.62.

4.4.4. Asymmetric addition of bis(triethylsilyl enol ether) to benzaldehyde. The same procedure described for the reaction between **2c** and benzaldehyde was carried out to prepare **8**. Asymmetric addition of **4** (391 mg, 1.00 mmol) to benzaldehyde (0.25 mL, 2.4 mmol) in the presence of **1d** prepared from *N*-(*p*-toluenesulfonyl)-(*S*)-tryptophan (77 mg, 0.22 mmol) and 3,5-bis(trifluoromethyl)-phenylboron dichloride (62 mg, 0.21 mmol) afforded **8** in 97% yield.

Compound **8**. Mp 120–122°C. $[\alpha]_D^{23}$=+124.1 (*c* 1.99, THF). The stereoselectivity was determined by chiral HPLC analysis using Chiralcel OD column (hexane/2-propanol=3:1), 0.4 mL/min, column temperature; 30°C, t_R=111 min (*S*,*S*), t_R=124 min (*meso*), t_R=167 min (*R*,*R*). ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.02 (s, 4H), 7.46–7.26 (m, 10H), 5.39–5.34 (m, 2H), 3.49–3.31 (m, 6H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 199.6, 142.9, 140.2, 128.9, 128.7, 128.1, 125.9, 70.2, 48.1. IR (KBr) 3456, 2901, 1677. Anal. calcd for $C_{24}H_{22}O_4$: C, 76.99; H, 5.92. Found: C, 76.70; H, 5.94%.

4.4.5. Asymmetric mono addition of bistriethylsilylenolether to benzaldehyde. Reaction of **4** (410 mg, 1.1 mmol) and benzaldehyde (0.12 mL, 1.18 mmol) in the presence of **1d** (0.23 mmol) was performed using the same procedure described for the reaction of **2c** with benzaldehyde. The product contained **9** (74%), **8** (17%), and diacetylbenzene (9%). The stereoselectivity (94% ee) of **9** was determined by chiral HPLC analysis using Chiralcel OD column (hexane/2-propanol=3:1), 0.4 mL/min, column temperature; 30°C, t_R=40 min (*S*)-**9**, t_R=44 min (*R*)-**9**. Mp 92–93°C. $[\alpha]_D^{23}$=+81.8 (*c* 1.99, THF). ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.03 (s, 4H), 7.46–7.26 (m, 5H), 5.37 (m, 1H), 3.50–3.32 (m, 3H), 2.65 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 199.7, 197.6, 143.0, 140.7, 139.9, 128.9, 128.8, 128.6, 128.1, 125.9, 70.2, 48.1, 27.1. IR (KBr) 3509, 2889, 1677, 1264.

4.5. Asymmetric aldol polymerization

General procedure. To a solution of chiral oxazaborolidinone catalyst (0.2 mmol) in propionitrile (2 mL) was added a mixture of bis(silyl enol ether) (1 mmol) and dialdehyde (1 mmol) in propionitrile (4 mL) at −78°C. The resulting mixture was stirred at −78°C for 1 h and allowed to warm to −20°C and stirred for another 4 h. After removal of the solvent under reduced pressure 2N HCl (5 mL) was added to the mixture and stirred at room temperature for 3 h. The reaction mixture was then poured into 300 mL of MeOH/H_2O (2:1) to precipitate the polymeric product. The white precipitate was filtered and dried in vacuo at 40°C for 8 h.

4.5.1. Asymmetric aldol polymerization of 4 and 7. According to the general method chiral polymer **16** was isolated as white powder.

Compound **16a**. ^{1}H NMR (DMSO-d_6) 8.06 (br, 4H), 7.43 (br, 8H), 5.41 (br, 2H), 5.13 (br, 2H), 3.55–3.27 (m, 4H), 0.49 (s, 6H). IR (KBr) 3471, 1681, 1208, 814. $[\alpha]_D$=+101, $[\Phi]_{405}$=+1670 (*c* 1.00, DMSO). Anal. calcd for $(C_{26}H_{26}O_4Si)_n$: C, 68.09; H, 5.71. Found: C, 67.89; H, 5.69.

Compound **16b**. ^{1}H NMR ($CDCl_3$) 8.03 (br, 4H), 7.45 (br, 8H), 5.32 (br, 2H), 3.37 (br, 6H), 0.63 (s, 4H), 0.24 (s, 12H). IR (KBr) 3476, 2953, 1681, 1207. $[\alpha]_D$=+76, $[\Phi]_{435}$=+1021 (*c* 1.00, THF). Anal. calcd for $(C_{30}H_{36}O_4Si_2)_n$: C, 69.73; H, 7.02. Found: C, 69.54; H, 6.98%.

4.5.2. Asymmetric polymerization of 5 and 7. According to the general method chiral polymer **17** was isolated as white powder.

Compound **17a**. ^{1}H NMR ($CDCl_3$) 7.90–7.39 (br, 16H), 5.33 (br, 2H), 3.50 (br, 2H), 3.33 (s, 4H), 0.59 (s, 6H), 0.54 (s, 6H). IR (KBr) 3466, 2956, 1677, 1212. $[\alpha]_D$=+78, $[\Phi]_{435}$=+1143 (*c* 1.00, THF). Anal. calcd for $(C_{34}H_{36}O_4Si_2)_n$: C, 72.30; H, 6.42. Found: C, 72.41; H, 6.48.

Compound **17b**. ^{1}H NMR ($CDCl_3$) 7.91–7.53 (br, 16H), 5.31 (br, 2H), 3.51 (br, 2H), 3.34 (s, 4H), 0.64 (s, 4H), 0.59 (s, 6H). IR (KBr) 3467, 2953, 1677, 1250. $[\alpha]_D$=+61, $[\Phi]_{435}$=+1058 (*c* 1.00, THF). Anal. calcd for $(C_{38}H_{46}O_4Si_3)_n$: C, 70.11; H, 7.12. Found: C, 70.01; H, 7.13%.

4.6. Preparation of *O*-acetylmandelate of aldol adduct 3c

O-acetylmandelate **19** was prepared according to the procedure described in the literature.[21]

Compound **19**. ^{1}H NMR ($CDCl_3$) 7.93–7.06 (m, 15H), 6.40 (t, *J*=6.7 Hz, 1H), 5.96 (s, 1H), 3.64 (dd, *J*=7.4, 17 Hz, 1H), 3.35 (dd, *J*=5.8, 17 Hz, 1H), 2.15 (s, 3H). ^{13}C NMR ($CDCl_3$) 195.79, 170.39, 167.74, 139.28, 136.81, 133.80, 133.62, 129.41, 128.92, 128.89, 128.61, 128.39, 128.16, 126.45, 74.54, 73.76, 45.21, 20.94. Anal. calcd for $C_{25}H_{22}O_5$: C, 74.61; H, 5.51. Found: C, 74.55; H, 5.47%.

4.7. Preparation of *O*-acetylmandelate of chiral polymer

To a solution of chiral polymer (113 mg) (*R*)-*O*-acetylmandelic acid (100 mg, 0.5 mmol) and dimethylaminopyridine (10 mg) in CH_2Cl_2 (2 mL) was added a solution of 1,3-dicyclohexylcarbodiimide (100 mg, 0.48 mmol) at −10°C. After being stirred at room temperature for 12 h precipitated urea was filtered and the solvent was evaporated. The residue was dissolved in CH_2Cl_2 and the remained urea was filtered again and the solvent was evaporated. The solid obtained was dissolved in THF and poured into MeOH/H_2O (1:1) to precipitate the polymer. After filtration the polymer was dried in vacuo at 40°C for 4 h. The optical purity of the chiral polymer was determined by the ratio of the diastereomeric methylene protons.

Compound **20a**. ^{1}H NMR (DMSO-d_6) 8.27–7.13 (br, 18H), 6.30 (s, 2H), 5.56 (s, 2H), 3.40 (br, 2H), 3.17 (br, 2H), 2.20 (s, 6H), 2.07 (s, 6H).

Compound **20b**. ^{1}H NMR ($CDCl_3$) 8.18–7.05 (br, 22H), 6.40 (s, 2H), 5.93 (s, 2H), 3.68 (br, 2H), 3.41 (br, 2H), 2.13 (s, 6H), 0.61 (t, 4H), 0.27s, 12H).

Compound **21a**. ^{1}H NMR ($CDCl_3$) 7.88–7.03 (br, 26H), 6.38 (t, 2H), 5.93 (s, 2H), 3.63 (br, 2H), 3.32 (br, 2H), 2.13 (s, 6H), 0.59 (s, 6H), 0.44 (s, 6H).

Compound **21b**. ^{1}H NMR ($CDCl_3$) 7.96–7.03 (br, 26H), 6.38 (t, 2H), 5.94 (s, 2H), 3.64 (br, 2H), 3.32 (br, 2H), 2.13 (s, 6H), 0.59 (s, 6H), 0.18 (t, 4H), 0.07 (s, 12H).

Acknowledgements

This work was partially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture of Japan. Financial support by the Amano Institute of Technology is also gratefully acknowledged.

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