Enantiomer-Selective Radical Polymerization of Bis(4-vinylbenzoate)s with Chiral Atom Transfer Radical Polymerization Initiating Systems

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ABSTRACT: We report a series of cyclopolymerizations of bis(4-vinylbenzoate) monomers through an atom transfer radical polymerization (ATRP) using chiral ligands. Cyclized polymers showing chiroptical properties were produced by polymerization of the racemic bifunctional monomer, *rac*-2,4-pentanediyl bis(4-vinylbenzoate) (*rac*-**1**), and enantiomerically unbalanced bifunctional monomers were recovered, providing substantial evidence for the enantiomer-selective polymerization of *rac*-**1** mediated through the ATRP with chiral ligands. A comparison between the enantiomerically pure monomers, (2*R*,4*R*)-2,4-pentanediyl bis(4-vinylbenzoate) (*RR*-**1**) and (2*S*,4*S*)-2,4-pentanediyl bis(4-vinylbenzoate) (*SS*-**1**), revealed a drastic discrepancy in the rates of their homopolymerizations during the ATRP. The enantiomeric copolymerization of *RR*-**1** and *SS*-**1** indicated that the monomer reactivity ratio of *RR*-**1** was higher than that of *SS*-**1** for the ATRP with chiral ligands. The results of both homopolymerizations and copolymerizations clearly demonstrate the propensity for incorporation of the *RR*-**1** enantiomer and thus the enantiomer-selective polymerization in this system. The monomer-structural effects on the enantiomer-selectivity were examined, and it was concluded that the chirality in the monomer is also essential for the enantiomer-selective polymerization as well as the chiral ligands for ATRP. Finally, the viability of the cyclopolymerization in the enantiomer-selective polymerization was proved using mono(4-vinylbenzoate) monomers incapable of cyclizing through the polymerization.

Introduction

Enantiomer-selective polymerization represents a stereospecific polymerization susceptible to stereochemistry in the monomer structures. In this polymerization, a favored enantiomer in the racemic monomer mixture is selectively incorporated into the polymers through the direction of chiral initiating systems. Considerable effort has focused on the development of enantiomer-selective polymerizations based on the design of catalysts, initiators, and monomers.[1−10] In general, coordination and ionic polymerizations have been used to advance such stereospecific polymerizations due to the promised interplay between macromolecules and incoming monomers at the polymerization active ends. This specificity is essentially mediated through chiral initiators and the local environment of the polymerization active ends. For example, Furukawa and coworkers demonstrated the enantiomer-selective polymerization through the coordination polymerization of racemic propylene oxides using $ZnEt_2$ and (+)-borneol and (−)-menthol systems.[1,2] Okamoto et al. reported that *S* isomers were preferably polymerized with a very high selectivity during the anionic polymerization of racemic (*R* and *S*)-α-methylbenzylmethacrylates using a cyclohexylmagnesium bromide/(−)-sparteine system.[3,4] The further development in this field will be highlighted in order to expand the enantiomer-selective polymerization using new synthetic methodologies.

Establishing the stereospecific polymerization including the enantiomer-selective polymerization through radical polymerizations is a challenging area in polymer synthetic chemistry.[11,12] The development of radical polymerizations with stereospecificities requires an increasingly high level of structural regulation throughout the polymerization due to the nature of the radical active end. Cyclopolymerizations featuring the cyclization of bifunctional monomers during the polymerization provide routes to control the stereochemistry of the polymer main chain through the radical polymerization. Wulff and co-workers[13,14] and Kakuchi and co-workers[15,16] have established a methodology to provide main-chain regulated polymers through the radical cyclopolymerization of a bifunctional monomer comprised of a chiral auxiliary. We have demonstrated that a racemic mixture of bifunctional methacrylates was polymerized by atom transfer radical polymerization (ATRP) using chiral ligands, and the system resulted in significant enantiomer selectivities.[17−19] Thus, the combination of cyclopolymerization and chiral initiating systems can provide the opportunity for the enantiomer-selective radical polymerizations due to the integrity and guidance of cyclization and chiral initiators. Progress toward increasingly stereospecific radical polymerizations through cyclopolymerization can be underscored by the design of monomers and ATRP ligands as well as the fundamental insight into the cyclopolymerization effects on the enantiomer selectivity.

Herein, we demonstrate the enantiomer selective polymerization of *rac*-2,4-pentanediyl bis(4-vinylbenzoate) (*rac*-**1**) using ATRP initiating systems consisting of methyl 2-bromoisobutylate (**2**), CuBr, and chiral ligands (Scheme 1). (−)-Sparteine (**3**), (*S*,*S*)-(+)-2,3-dimethoxy-1,4-bis(dimethylamino)butane (**4**), 2,6-bis[4*R*-(+)-isopropyl-2-oxazoline-2-yl)pyridine (*RR*-**5**), and 2,6-bis[4*S*-(-)-isopropyl-2-oxazoline-2-yl)pyridine (*SS*-**5**) were used as the chiral ligands to impart the initiating systems with

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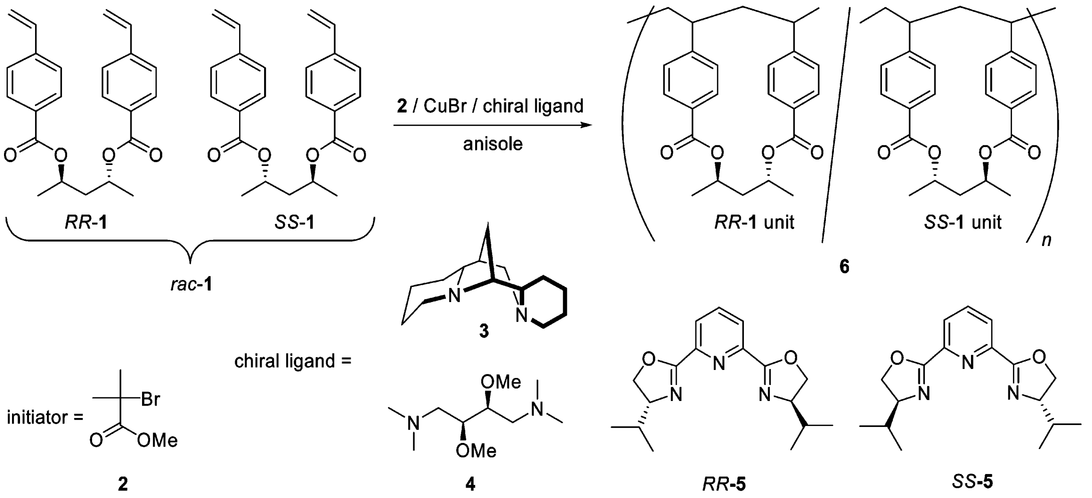
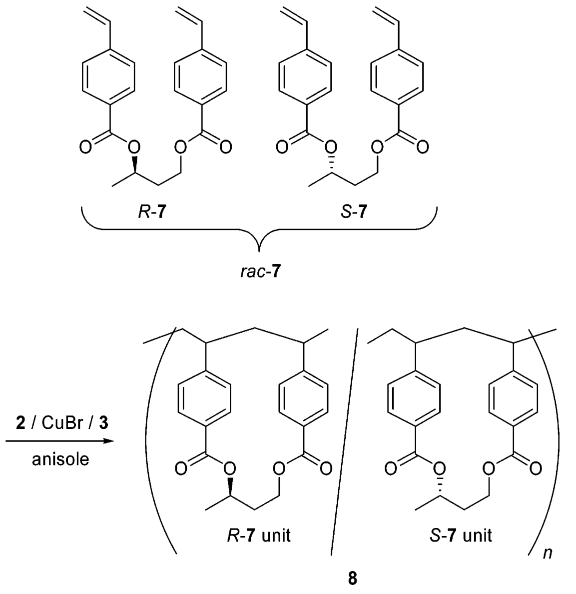
Scheme 1. Polymerization of *rac*-2,4-Pentanediyl Bis(4-vinylbenzoate) (*rac*-1) Using ATRP Initiating Systems Consisting of Methyl 2-Bromoisobutylate (2), CuBr, and Chiral Ligands Including (−)-Sparteine (3), (*S*,*S*)-(+)-2,3-Dimethoxy-1,4-bis(dimethylamino)butane (4), 2,6-Bis[4*R*-(+)-isopropyl-2-oxazoline-2-yl)pyridine (*RR*-5), and 2,6-Bis[4*S*-(−)-isopropyl-2-oxazoline-2-yl)pyridine (*SS*-5), Producing Polymer 6

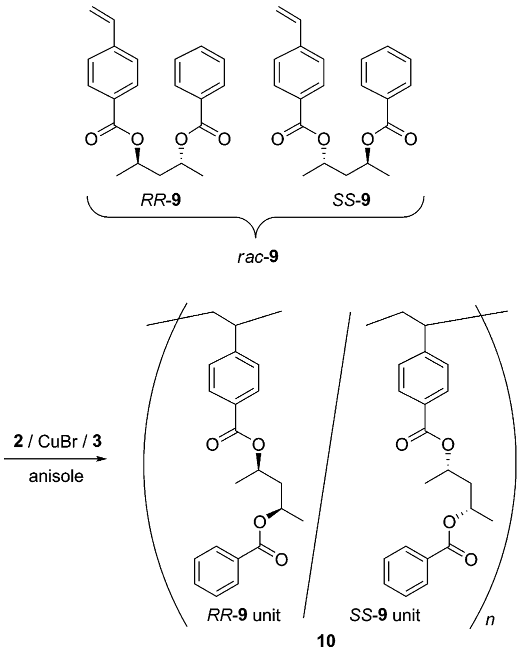


Scheme 2. Polymerization of *rac*-1,3-Butanediyl Bis(4-vinylbenzoate) (*rac*-7) Using ATRP Initiating Systems Consisting of Methyl 2-Bromoisobutylate (2), CuBr, and (−)-Sparteine (3), Producing Polymer 8



a chiral selectivity. The enantiomerically pure monomers, (2*R*,4*R*)-2,4-pentanediyl bis(4-vinylbenzoate) (*RR*-**1**) and (2*S*,4*S*)-2,4-pentanediyl bis(4-vinylbenzoate) (*SS*-**1**), were individually homopolymerized by the ATRP with chiral ligands to determine the rates of polymerization for each enantiomer, demonstrating the drastic difference in the rates and thus the enantiomer selective polymerization. The copolymerization with a variable ratio of *RR*-**1** and *SS*-**1** resulted in all possible rates of polymerization in this system, providing insightful information about the enantiomer-selective radical polymerization. Subtle structural effects on the enantiomer-selectivities were revealed through cyclopolymerization of *rac*-1,3-butanediyl bis(4-vinylbenzoate) (*rac*-**7**) as depicted in Scheme 2. To further explore the cyclopolymerization effects on the enantiomer selective polymerization, the corresponding racemic monofunctional monomer, *rac*-(*R*,*S*)-2-[(*R*,*S*)-4-benzoyl]pentyl(4-vinylbenzoate) (*rac*-**9**) was polymerized for the cyclopolymerization control experiment (Scheme 3).

Scheme 3. Polymerization of *rac*-(*R*,*S*)-2-[(*R*,*S*)-4-Benzoyl]pentyl(4-vinylbenzoate) (*rac*-9) Using ATRP Initiating Systems Consisting of Methyl 2-Bromoisobutylate (2), CuBr, and (−)-Sparteine (3) to Produce Polymer 10



Experimental Section

Materials. (−)-Sparteine (Aldrich, 99%), (2*S*,3*S*)-(+)-2,3-dimethoxy-1,4-bis(dimethylamino)butane (AZmax Co., Japan, >95%), pyridine (Kanto Chemical Co., Japan, >99.5%), and methyl 2-bromoisobutylate (Wako Pure Chemical Industries, Japan, 98%) were distilled over CaH_2. 2,6-Bis[4*R*-(+)-isopropyl-2-oxazoline-2-yl)pyridine (Aldrich, 99%) and 2,6-bis[4*S*-(-)-isopropyl-2-oxazoline-2-yl)pyridine (Aldrich, 99%) were dried in vacuo before use. CuBr (Junsei Chemical Co., Japan, 99%) was purified by stirring in acetic acid, filtering, and washing with ethanol.[20] α,α′-Azobisisobutyronitrile (AIBN, Kanto Chemical Co., Japan, >97%) was recrystallized from methanol. *rac*-2,4-Pentanediol[17] and 4-vinylbenzoylchloride[21] were prepared according to literature procedures. (2*R*,4*R*)-2,4-Pentanediol (Kanto Chemical Co., Japan, >99.0%), (2*S*,4*S*)-2,4-pentanediol (Kanto Chemical Co., Japan, >99.0%), *rac*-1,3-butanediol (Kanto Chemical Co., Japan, >98.0%), dry anisole (Aldrich, 99.7%, water content < 0.002%), dicyclohexylcarbodiimide (DCC, Wako Pure Chemical Industries, Japan, >95.0%), dimethylaminopyridine (DMAP, Wako Pure Chemical Industries, Japan, >99.0%), and benzoic acid (Kanto Chemical Co., Japan, >99.5%) were used as received.

Measurements. The ^{1}H (400 MHz) and ^{13}C NMR (100 MHz) spectra were recorded by a JEOL JNM-A400II instrument. Elemental analysis was conducted using a Yanaco CHN corder MT-6 (Center for Instrumental Analysis, Hokkaido University). The size exclusion chromatography (SEC) was performed at 40 °C using a Jasco GPC-900 system equipped two Shodex KF-804L columns (column size, 8 mm × 300 mm; pore size, linear; bead size, 7 μm; exclusion limit, 4×10^5) and a Waters Ultrastyragel column (column size, 7.8 mm × 300 mm; pore size, linear; bead size, 7 μm; exclusion limit, 1×10^7) in tetrahydrofuran (THF) at the flow rate of 0.8 mL min^{-1}. The number-average molecular weight (M_n) and molecular weight distribution (M_w/M_n) were calculated on the basis of a polystyrene calibration. The specific rotations were measured in chloroform using a Jasco DIP 1000 digital polarimeter with a Hg lamp (wavelength, 435 nm). The enantiomeric excess (ee) of the recovered monomers and monomer conversion were determined using a high-performance liquid chromatography (HPLC) system (PU-980 Intelligent HPLC pump and UV-975 Intelligent UV detector) equipped with a Daicel CHIRALCEL OD column (hexane/isopropanol = 100/1 (v/v); flow rate, 1.0 mL min^{-1}). The polymerization mixtures were prepared in an MBRAUN stainless steel glovebox equipped with a gas purification system (molecular sieves and copper catalyst) and dry argon atmosphere (H_2O, O_2 < 1 ppm).

***rac*-2,4-Pentanediyl Bis(4-vinylbenzoate) (*rac*-1).** 4-Vinylbenzoylchloride (20 g, 0.12 mol) was slowly added to a solution of *rac*-2,4-pentanediol (2.6 g, 25 mmol) in dry pyridine (70 mL) at 0 °C. After being stirred for 1 day at ambient temperature, the reaction mixture was quenched with water (100 mL) and extracted three times with diethyl ether. The extracted solution was washed with 1 N HCl (200 mL), 0.5 M NaOH (100 mL), and water (200 mL). After the ether solution was dried over anhydrous $MgSO_4$, the solvent was removed, and then the residue was purified by column chromatography on silica gel with hexane/ethyl acetate (8.5/1.5, v/v) to give *rac*-**1** as a colorless viscous liquid. Yield: 8.0 g (94%). ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.91 (d, J = 8.3 Hz, 4H, aromatic H meta to $-CH{=}CH_2$), 7.34 (d, J = 8.3 Hz, 4H, aromatic H ortho to $-CH{=}CH_2$), 6.68 (dd, J_{trans} = 17.6 Hz, J_{cis} = 10.7 Hz, 2H, $-CH{=}$), 5.79 (d, J_{trans} = 17.5 Hz, 2H, $={CH_2}$), 5.32 (d, J_{cis} = 10.7 Hz, 2H, $={CH_2}$), 5.34∼5.27 (m, 2H, CH), 2.06 (t, J = 6.2 Hz, 2H, CH_2), 1.38 (d, J = 6.3 Hz, 6H, CH_3). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) = 165.3 (C═O), 141.5 (aromatic $C-CH{=}CH_2$), 135.8 ($={CH}-$), 129.6 (aromatic C meta to $-CH{=}CH_2$), 129.4 (aromatic $C-C{=}O$), 125.7 (aromatic C ortho to $-CH{=}CH_2$), 116.0 ($CH_2{=}$), 67.9 (CH), 41.8 (CH_2), 20.2 (CH_3). Anal. Calcd for $C_{23}H_{24}O_4$ (364.4): C, 75.80; H, 6.64. Found: C, 75.86; H, 6.82.

(2*R*,4*R*)-2,4-Pentanediyl Bis(4-vinylbenzoate) (*RR*-1). A similar procedure for *rac*-**1** was applied to (2*R*,4*R*)-2,4-pentanediol (2.6 g, 25 mmol) in dry pyridine (40 mL) and 4-vinylbenzoylchloride (12 g, 74 mmol) to give *RR*-**1** as a viscous liquid. Yield: 7.3 g (80%). ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.91 (d, J = 8.3 Hz, 4H, aromatic H meta to $-CH{=}CH_2$), 7.36 (d, J = 8.3 Hz, 4H, aromatic H ortho to $-CH{=}CH_2$), 6.69 (dd, J_{trans} = 17.7 Hz, J_{cis} = 10.9 Hz, 2H, $-CH{=}$), 5.80 (d, J_{trans} = 17.6 Hz, 2H, $={CH_2}$), 5.34 (d, J_{cis} = 11.0 Hz, 2H, $={CH_2}$), 5.33∼5.27 (m, 2H, CH), 2.07 (t, J = 6.3 Hz, 2H, CH_2), 1.39 (d, J = 6.3 Hz, 6H, CH_3). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) = 165.4 (C═O), 141.5 (aromatic $C-CH{=}CH_2$), 135.8 ($={CH}-$), 129.6 (aromatic C meta to $-CH{=}CH_2$), 129.5 (aromatic $C-C{=}O$), 125.8 (aromatic C ortho to $-CH{=}CH_2$), 116.0 ($CH_2{=}$), 68.0 (CH), 41.9 (CH_2), 20.2 (CH_3). Anal. Calcd for $C_{23}H_{24}O_4$ (364.4): C, 75.80; H, 6.64. Found: C, 75.76; H, 6.61. $[\alpha]^{25}_{435} = -513.4°$ (*c* 1.0, $CHCl_3$, 25 °C).

(2*S*,4*S*)-2,4-Pentanediyl Bis(4-vinylbenzoate) (*SS*-1). The procedures were reported in a previous paper.[22]

***rac*-1,3-Butanediyl Bis(4-vinylbenzoate) (*rac*-7).** A similar procedure for *rac*-**1** was applied to *rac*-1,3-butanediol (3.6 g, 40 mmol) in dry pyridine (60 mL) and 4-vinylbenzoylchloride (15 g, 90 mmol) to give *rac*-**10** as a viscous liquid. Yield: 12.1 g (83%). ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.97 (d, J = 8.3 Hz, 2H, aromatic H meta to $-CH{=}CH_2$), 7.95 (d, J = 8.4 Hz, 2H, aromatic H meta to $-CH{=}CH_2$), 7.40 (d, J = 8.3 Hz, 2H, aromatic H ortho to $-CH{=}CH_2$), 7.38 (d, J = 8.2 Hz, 2H, aromatic H ortho to $-CH{=}CH_2$), 6.71 (dd, J_{trans} = 17.6 Hz, J_{cis} = 10.7 Hz, 1H, $-CH{=}$), 6.70 (dd, J_{trans} = 17.5 Hz, J_{cis} = 10.8 Hz, 1H, $-CH{=}$), 5.82 (d, J_{trans} = 17.6 Hz, 2H, $={CH_2}$), 5.35 (d, J_{cis} = 10.8 Hz, 2H, $={CH_2}$), 5.42−5.31 (m, 1H, OCH), 4.50−4.37 (m, 2H, OCH_2), 2.24−2.06 (m, 2H, CH_2), 1.42 (d, J = 6.3 Hz, 3H, CH_3). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) = 166.2 (C═O), 165.7 (C═O), 141.9, (aromatic $C-CH{=}CH_2$), 136.0 ($={CH}-$), 129.8 (aromatic C meta to $-CH{=}CH_2$), 129.6 (aromatic $C-C{=}O$), 129.2 (aromatic $C-C{=}O$), 126.0 (aromatic C ortho to $-CH{=}CH_2$), 116.4 ($CH_2{=}$), 68.8 (CH), 61.4 (OCH_2), 35.0 (CH_2), 20.2 ($-CH_3$). Anal. Calcd for $C_{22}H_{22}O_4$ (350.4): C, 75.44; H, 6.33. Found: C, 75.31; H, 6.44.

***rac*-(*R*,*S*)-2-[(*R*,*S*)-4-Benzoyl]pentyl(4-vinylbenzoate) (*rac*-9).** The procedure is analogous to those reported in previous papers.[23] A mixture of dicyclohexylcarbodiimide (5.7 g, 27 mmol), dimethylaminopyridine (0.24 mg, 2.0 mmol), and benzoic acid (3.1 g, 25 mmol) in dry THF (30 mL) was slowly added to a solution of *rac*-2,4-pentanediol (3.9 g, 38 mmol) in dry THF (70 mL). After stirring overnight, the reaction mixture was filtered twice and then washed with 1 N HCl, a saturated aqueous solution of $NaHCO_3$, and brain. The crude product was extracted with $CHCl_3$ and purified by short column chromatography on silica gel with $CHCl_3$/AcOEt (9/1, v/v) to afford the monoester product. Yield: 2.2 g (42%, based on benzoic acid). 4-Vinylbenzoyl chloride in dry pyridine was slowly added to a solution of the monoester product (2.2 g, 11 mmol) at 0 °C. A similar procedure described for *rac*-**1** was applied to the reaction mixture to afford *rac*-**9** as a colorless viscous liquid. Yield: 2.9 g (34%, total yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 7.98∼7.95 (d, J = 8.2 Hz, 2H, aromatic H ortho to C═O), 7.91 (d, J = 8.4 Hz, 2H, aromatic H meta to $-CH{=}CH_2$), 7.44∼7.40 (m, 2H, aromatic H meta to C═O), 7.33∼7.29 (m, 3H, aromatic H meta to C═O + aromatic H para to C═O), 6.66 (dd, J_{trans} = 17.6 Hz, J_{cis} = 10.9 Hz, 1H, $-CH{=}$), 5.77 (d, J_{trans} = 17.5 Hz, 1H, $={CH_2}$), 5.29 (d, J_{cis} = 10.8 Hz, 1H, $={CH_2}$), 5.34∼5.27 (m, 2H, CH), 2.03 (t, J = 6.2 Hz, 2H, CH_2), 1.36 (d, J = 6.3 Hz, 6H, CH_3). ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) = 165.8 (C═O), 165.5 (C═O), 141.6 (aromatic $C-CH{=}CH_2$), 135.9 ($={CH}-$), 132.6 (aromatic C para to C═O), 130.4 (aromatic $C-C{=}O$), 129.7 (aromatic C ortho to C═O), 129.5 (aromatic C para to $-CH{=}CH_2$), 129.4 (aromatic C ortho to C═O), 128.1 (aromatic C meta to C═O), 125.8 (aromatic C ortho to $-CH{=}CH_2$), 116.1 ($CH_2{=}$), 68.1 (CH), 68.0 (CH), 42.0 (CH_2), 20.3 (CH_3). Anal. Calcd for $C_{21}H_{22}O_4$ (338.40): C, 74.54; H, 6.55, Found; C, 74.00; H, 6.26.

Polymerization. All polymerizations were carried out under an argon atmosphere in a dry test tube capped with a screw top. A typical procedure is as follows: In a glovebox (H_2O, O_2 < 1 ppm), CuBr (6.0 mg, 4.2×10^{-2} mmol) and **3** (19.4 mg, 8.5×10^{-2} mmol) were added to a dry anisole solution of *rac*-**1** (0.10 mol L^{-1}, 20 mL). After the system became homogeneous, **2** (3.6 mg, 2.3×10^{-2} mmol) was added, and then nine aliquots (2 mL each) of the solution mixture were quickly separated in the test tubes and then heated at 90 °C outside the glovebox for 72 h. Upon exposure of the polymerization solution to air and freezing with liquid nitrogen, the polymerization totally stopped. A 20 μL aliquot of the polymerization mixture was added to the eluent for the HPLC (0.5 mL) and filtered through a 0.25 μm membrane filter. The monomer conversion and the enantiomeric excess (ee) were determined by HPLC. The rest of the combined solution was quickly passed twice through an alumina column in order to remove the metal catalyst, and then the solvent was evaporated under reduced pressure. The residue was purified by reprecipitation with methanol/chloroform and dried in vacuo to give polymer **6**. Yield: 19 mg (25%). Conversion: 29%. ee of recovered monomer: 13.0%. M_n(M_w/M_n) = 10 400 (1.18). $[\alpha]_{435} = -17.8°$ (*c* 1.0, $CHCl_3$, room temp). ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = 8.15∼4.83 (br, 10H, aromatic H + $-CH(CH_3)O-$), 2.63~0.76 (br, 14H, $-OCH(CH_3)CH_2CH(CH_3)O-$ + $-CH_3$ + $-CH-$ in the main chain + $-CH_2-$ in the main chain).

Results and Discussion

Enantiomer-Selective Cyclopolymerization of *rac*-1 Using 2/CuBr/Chiral Ligands. *rac*-2,4-Pentanediyl bis(4-vinylbenzoate) (*rac*-**1**), an equimolar mixture of (2*R*,4*R*)-2,4-pentanediyl bis(4-vinylbenzoate) (*RR*-**1**) and (2*S*,4*S*)-2,4-pentanediyl bis(4-vinylbenzoate) (*SS*-**1**) enantiomers, was polymerized through the ATRP consisting of methyl 2-bromoisobutylate (**2**), CuBr, and chiral ligands including (−)-sparteine (**3**), (*S*,*S*)-(+)-2,3-dimethoxy-1,4-bis(dimethylamino)butane (**4**), 2,6-bis[4*R*-(+)-isopropyl-2-oxazoline-2-yl)pyridine (*RR*-**5**), and 2,6-bis[4*S*-(−)-isopropyl-2-oxazoline-2-yl)pyridine (*SS*-**5**) as illustrated in Scheme 1. All the polymerizations were performed in anisole at 90 °C with the monomer concentration ($[rac\text{-}\mathbf{1}]_0$) of 0.1 mol L^{-1} and homogeneously proceeded. Aliquots of the polymerization solution were injected into the chiral HPLC system to estimate the monomer conversion and the enantiomeric excess (ee) of the unpolymerized monomers.

Figure 1 shows the ^{13}C NMR spectrum of the resultant polymer **6** from *rac*-**1**. Disappearance of the characteristic peaks for the vinyl groups at 116 and 126 ppm for polymer **6** essentially demonstrates the high fidelity of cyclization during the polymerization, and thus an ideal cyclopolymerization. Runs 1−4 in Table 1 show the results of the ATRP of *rac*-**1** using diverged chiral initiators (**3**, **4**, *RR*-**5**, and *SS*-**5**) and characterizations of the resulting polymers **6**. The number-average molecular weight (M_n) and molecular weight distribution (M_w/M_n) of polymer **6** ranged from 10 400 to 101 000 and from 1.18 to 1.79, respectively. It should be noted that the ATRP with chiral ligand **3** produced **6** with the low M_w/M_n of 1.18.

The enantiomeric imbalance of the left-over monomers and chiroptical activity of the resultant polymers indicated that the chiral ligands used were able to promote the enantiomer-selective polymerization of the racemic bis(4-vinylbenzoate)s. From the system with chiral ligand **3**, the *RR*-**1** enantiomer was preferentially polymerized with the recovered monomer of 13.0% ee at a 29% monomer conversion, and the resulting polymer **6** showed the $[\alpha]_{435}$ of −17.8° (run 1). Another chiral ligand **4** displayed a low enantiomeric selectivity in the recovered monomer of 1.3% ee (run 2). The resulting polymer **6** from this ligand showed low specific rotations in comparison to that from ligand **3**, substantially reflecting the low selectivity. An enantiomeric pair of oxazoline ligands (*RR*-**5** and *SS*-**5**) resulted in very coinciding chiroptical properties in the cyclized polymers and left over monomers. By using *RR*-**5** as the chiral ligand, the *RR*-**1** enantiomer was preferentially polymerized with a 6.9% ee of the recovered monomers, and the obtained polymer **6** showed a specific optical rotation of $[\alpha]_{435} = -5.2°$ ($CHCl_3$, $c = 1.0$, run 3). On the contrary, the ATRP system with oxazoline derivatives *SS*-**5** resulted in the preferential incorporation of the *SS*-**1** enantiomer with a 7.5% ee for the recovered monomers and provided **6** with $[\alpha]_{435} = +5.5°$ ($CHCl_3$, $c = 1.0$, run 4).

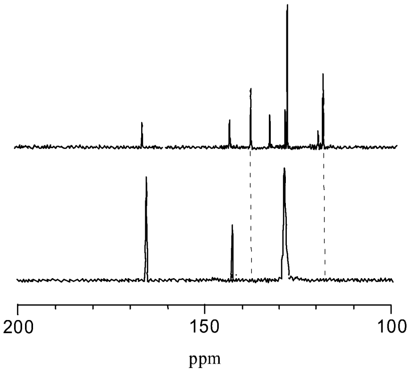


Figure 1. ^{13}C NMR (100 MHz) spectra of *rac*-2,4-pentanediyl bis(4-vinylbenzoate) (*rac*-**1)** (upper) and polymer **6** obtained through the polymerization of *rac*-**1** using ATRP initiating system consisting of methyl 2-bromoisobutylate (**2**), CuBr, and (−)-sparteine (**3**) (lower). Refer to Scheme 1 for structures of *rac*-**1**, **2**, and **3**.

To determine the integral role of ATRP in the systems, the radical polymerization of *rac*-**1** using α,α′-azobisisobutyronitrile (AIBN) with ligand **3** was carried out. The obtained polymer and left-over monomers showed no chiroptical properties, and therefore, the ATRP is essential for the enantiomer selective polymerization.

Kinetic Study in Enantiomer-Selective Polymerization of *rac*-1 Using 2/CuBr/3. Given that (−)-sparteine (**3**) is effective for the enantiomeric selectivity, we further explored the enantiomer-selective radical polymerization of *rac*-**1** using **3** to provide kinetic studies of this system. Figure 2A shows the plots for the M_n and M_w/M_n of polymers **6** as a function of the monomer conversion during the polymerization of *rac*-**1** using **2**/CuBr/**3** ($[rac\text{-}\mathbf{1}]_0/[\mathbf{2}]_0/[\mathrm{CuBr}]_0/[\mathbf{3}]_0 = 100/1/2/4$). The M_n values linearly increased with the increasing monomer conversion with the relatively low M_w/M_n values ranging between 1.14 and 1.25, providing evidence for the controlled radical polymerization. Figure 2B shows the kinetic plots for the polymerization of *rac*-**1** using the **2**/CuBr/**3**, indicating the sharp contrast in the rate of monomer consumption between the enantiomers. As expected, the *RR*-**1** enantiomer was polymerized faster than the *SS*-**1** enantiomer, clearly demonstrating the enantiomer selective polymerization.

Homopolymerization of *RR*-1 and *SS*-1 Using 2/CuBr/3. To better understand the results for the polymerization of *rac*-

Table 1. Enantiomer-Selective Cyclopolymerization of Racemic Monomers, *rac*-2,4-Pentanediyl Bis(4-vinylbenzoate) (*rac*-1), *rac*-1,3-Butanediyl Bis(4-vinylbenzoate) (*rac*-7), and *rac*-(*R*,*S*)-2-[(*R*,*S*)-4-Benzoyl]pentyl(4-vinylbenzoate) (*rac*-9), Using the ATRP Initiating System Consisting of Methyl 2-Bromoisobutylate (2), CuBr, and Chiral Ligands[a]

run	monomer	ligand	conversion[b] (%)	preferentially polymerized monomer[b]	ee of recovered monomer[c] (%)	obtained polymer	$M_n(M_w/M_n)$[d]	$[\alpha]_{435}$[e] (deg)
1	*rac*-**1**	**3**	29	*RR*-**1**	13.0	6	10 400 (1.18)	−17.8
2	*rac*-**1**	**4**	17	*RR*-**1**	1.3	6	101 000 (1.54)	−3.8
3	*rac*-**1**	*RR*-**5**	23	*RR*-**1**	6.9	6	43 800 (1.68)	−5.2
4	*rac*-**1**	*SS*-**5**	26	*SS*-**1**	7.5	6	39 400 (1.79)	+5.5
5	*rac*-**7**	**3**	28	*R*-**7**	6.4	8	14 800 (1.37)	−12.6
6	*rac*-**9**	**3**	22			10	8 600 (1.22)	

[a] $[\mathrm{monomer}]_0 = 0.1$ mol L^{-1}; $[\mathrm{monomer}]_0/[\mathbf{2}]_0/[\mathrm{CuBr}]_0/[\mathrm{ligand}]_0 = 100/1/2/4$; solvent, anisole; temperature, 90 °C. [b] Monomer conversion determined by HPLC equipped with a CHIRALCEL OD column. [c] Enantiomeric excess of recovered monomer determined by HPLC equipped with a CHIRALCEL OD column. [d] Number-average molecular weight (molecular weight distribution) determined by SEC in THF using polystyrene standards. [e] Specific rotation measured using a wavelength of 435 nm in $CHCl_3$ (c 1.0, room temp).

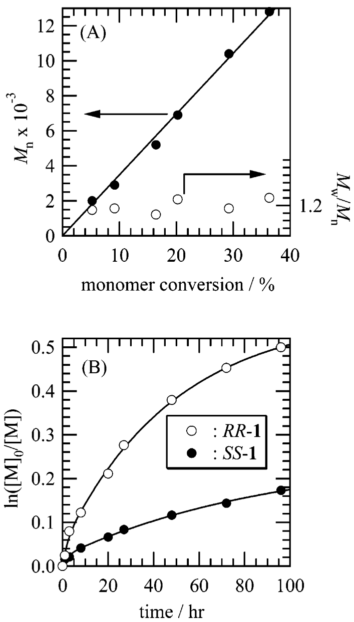


Figure 2. (A) Plots of the number-average molecular weight (M_n) and molecular weight distribution (M_w/M_n) of polymers **6** obtained through the polymerization of *rac*-2,4-pentanediyl bis(4-vinylbenzoate) (*rac*-**1)** using ATRP system consisting of methyl 2-bromoisobutylate (**2**), CuBr, and (−)-sparteine (**3**) as a function of monomer conversion and (B) kinetic plots for (2*R*,4*R*)-2,4-pentanediyl bis(4-vinylbenzoate) (*RR*-**1**) and (2*S*,4*S*)-2,4-pentanediyl bis(4-vinylbenzoate) (*SS*-**1**) enantiomers in the polymerization of *rac*-**1** using ATRP system consisting of **2**, CuBr, and **3** ([*rac*-**1**]$_0$ = 0.1 mol L^{-1}; [*rac*-**1**]$_0$/[**2**]$_0$/[CuBr]$_0$/[**3**]$_0$ = 100/1/2/4; temp = 90 °C). Refer to Scheme 1 for structures of *rac*-**1**, *RR*-**1**, *SS*-**1**, **2**, and **3**.

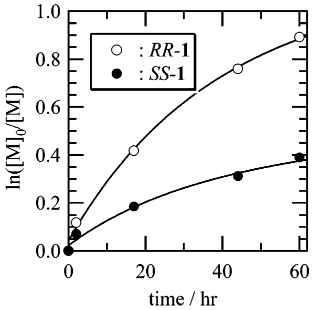


Figure 3. Kinetic plots for the homopolymerizations of (2*R*,4*R*)-2,4-pentanediyl bis(4-vinylbenzoate) (*RR*-**1**) and (2*S*,4*S*)-2,4-pentanediyl bis(4-vinylbenzoate) (*SS*-**1**) using ATRP initiating system consisting of methyl 2-bromoisobutylate (**2**), CuBr, and (−)-sparteine (**3**) ([*RR*-**1**]$_0$ = [*SS*-**1**]$_0$ = 0.1 mol L^{-1}; [*RR*-**1** or *SS*-**1**]$_0$/[**2**]$_0$/[CuBr]$_0$/[**3**]$_0$ = 100/1/2/4; temp = 90 °C). Refer to Scheme 1 for structures of *RR*-**1**, *SS*-**1**, **2**, and **3**.

1, we examined the homopolymerizations of (2*R*,4*R*)-2,4-pentanediyl bis(4-vinylbenzoate) (*RR*-**1**) and (2*S*,4*S*)-2,4-pentanediyl bis(4-vinylbenzoate) (*SS*-**1**) using **2**/CuBr/**3** ([*RR*-**1** or *SS*-**1**]$_0$/[**2**]$_0$/[CuBr]$_0$/[**3**]$_0$ = 100/1/2/4), that produced enantiomerically pure polymers. Figure 3 shows the kinetic plots for the individual homopolymerizations. The polymerization rate for *RR*-**1** was significantly faster than that of *SS*-**1**, supporting the results observed from the enantiomer-selective polymerization of *rac*-**1** with **3**. We estimated the homopolymerization rates for the *RR*-**1** and *SS*-**1** monomers (K_{RR} and K_{SS}) to be 2.93 × 10^{-2} and 1.37 × 10^{-2} h^{-1}, respectively, from the initial slopes in Figure 3.

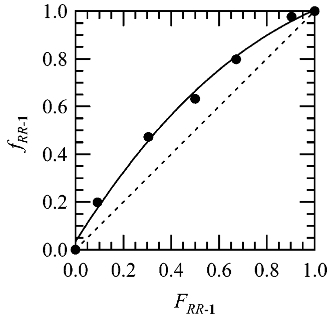


Figure 4. Composition curve for the copolymerization of (2*R*,4*R*)-2,4-pentanediyl bis(4-vinylbenzoate) (*RR*-**1**) and (2*S*,4*S*)-2,4-pentanediyl bis(4-vinylbenzoate) (*SS*-**1**) using ATRP initiating system consisting of methyl 2-bromoisobutylate (**2**), CuBr, and (−)-sparteine (**3**) ([*RR*-**1** + *SS*-**1**]$_0$ = 0.1 mol L^{-1}; [*RR*-**1**+ *SS*-**1**]$_0$/[**2**]$_0$/[CuBr]$_0$/[**3**]$_0$ = 100/1/2/4; temp = 90 °C). See Scheme 1 for structures of *RR*-**1**, *SS*-**1**, **2**, and **3**.

Enantiomeric Copolymerization of *RR*-1 and *SS*-1 Using 2/CuBr/3. The homopolymerization rates for *RR*-**1** and *SS*-**1** through the ATRP with ligand **3**, K_{RR} and K_{SS}, were demonstrated from the homopolymerizations of the corresponding enantiomerically pure monomers. Determining the polymerization rates between the enantiomers (K_{RS} and K_{SR}) provided further insights into the enantiomer-selective polymerization. In order to quantify K_{RS} and K_{SR}, the enantiomeric copolymerizations of *RR*-**1** and *SS*-**1** were performed for a variable ratio of *RR*-**1** and *SS*-**1** through the ATRP using **2**/CuBr/**3**. The enantiomeric copolymerizations were carried out at the total monomer concentration of 0.1 mol L^{-1} using [*RR*-**1** + *SS*-**1**]$_0$/[**2**]$_0$/[CuBr]$_0$/[**3**]$_0$ = 100/1/2/4 to afford copolymers featuring a variable ratio of *RR*-**1** and *SS*-**1** units. Figure 4 shows the copolymerization composition curve, where F_{RR-1} and f_{RR-1} denote the molar fraction of *RR*-**1** in the total monomer feed and that of the *RR*-**1** unit in the copolymer, respectively. The molar fractions of the *RR*-**1** units in the copolymers were higher than those of the *SS*-**1** units for every monomer feed. For example, the copolymerization using the F_{RR-1} of 0.30 produced the copolymer with the f_{RR-1} of 0.47. Thus, it is found that the copolymerization reactivity of *RR*-**1** was higher than that of *SS*-**1** for the enantiomeric copolymerization of *RR*-**1** and *SS*-**1** using **2**/CuBr/**3**. The quantitative treatment of the observed curves using the expanded Kelen−Tüdös method[24] provided the monomer reactivity ratios for *RR*-**1** (r_{RR-1}) and *SS*-**1** (r_{SS-1}) of 1.6 and 0.40, respectively. On the basis of these monomer reactivity ratios, the polymerization rates between the enantiomers were finally quantified to be 1.83 × 10^{-2} and 3.43 × 10^{-2} h^{-1} for K_{RS} and K_{SR}, respectively. The complete results for the polymerization rates are again clearly demonstrating the propensity for the incorporation of *RR*-**1** and thus the enantiomer selective polymerization of this system.

Monomer-Structural Effects on the Enantiomer-Selectivity. From kinetic studies of the homopolymerizations of the *RR*-**1** and *SS*-**1** monomers and those of their enantiomeric copolymerizations, significantly higher polymerization rates for *RR*-**1** over *SS*-**1** were demonstrated in the ATRP with ligand **3**. We next focused on determining the monomer-structural effects of the enantiomer-selectivity. To investigate such effects, *rac*-1,3-butanediyl bis(4-vinylbenzoate) (*rac*-**7)** was prepared and polymerized using the ATRP initiating system consisting of **2**/CuBr/**3** (Scheme 2). Run 5 in Table 1 shows representative results for the cyclopolymerization of *rac*-**7** **(**[*rac*-**7**]$_0$/[**2**]$_0$/[CuBr]$_0$/[**3**]$_0$ = 100/1/2/4**)**. The 6.4% ee of the recovered monomers was observed at the conversions of 28%. The obtained polymer **8** with the M_n (M_w/M_n) of 14 800 (1.37) showed the [α]$_{435}$ value of −12.6°. As expected, ligand **3** also resulted in the enantiomer-selective ATRP for *rac*-**7**, in which the *R*-**7** unit was more enriched in **8**. However, monomer **7**

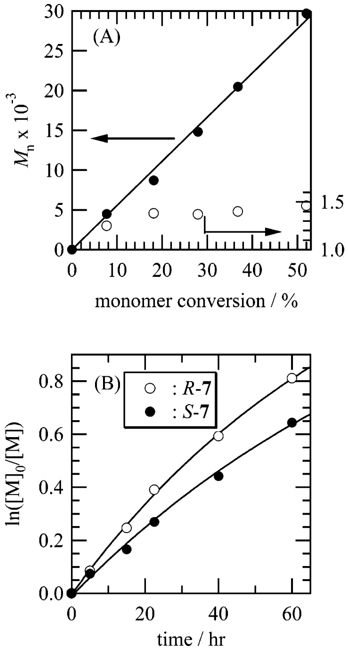


Figure 5. (A) Plots of the number-average molecular weight (M_n) and molecular weight distribution (M_w/M_n) of polymers **8** obtained through the polymerizations of *rac*-1,3-butanediyl bis(4-vinylbenzoate) (*rac*-**7)** using ATRP initiating system consisting of methyl 2-bromoisobutylate (**2**), CuBr, and (−)-sparteine (**3**) as a function of monomer conversion and (B) kinetic plots for the polymerizations of (*R*)-1,3-butanediyl bis(4-vinylbenzoate) (*R*-**7**) and (*S*)-1,3-butanediyl bis(4-vinylbenzoate) (*S*-**7**) enantiomers in the polymerization of *rac*-**7** using ATRP initiating system consisting of **2**, CuBr, and **3** ($[rac\text{-}\mathbf{7}]_0 = 0.1$ mol L^{-1}; $[rac\text{-}\mathbf{7}]_0/[\mathbf{2}]_0/[\text{CuBr}]_0/[\mathbf{3}]_0 = 100/1/2/4$; temp = 90 °C). Refer to Scheme 2 for structures of *rac*-**7**, *R*-**1**, and *S*-**1**, and Scheme 1 for those of **2** and **3**.

provided a much lower ee than monomer **1** under comparable conditions.

Figure 5A shows the plots for the M_n and M_w/M_n of **8** as a function of the monomer conversion for the polymerization of *rac*-**7**. The M_n values linearly increased with the increasing monomer conversion, whereas the M_w/M_n values were relatively low between 1.25 and 1.46. Figure 5B shows the kinetic plots for the polymerization of *rac*-**7**, indicating that the *R*-**7** enantiomer was preferentially polymerized over the *S*-**7** enantiomer. However, the enantiomer-selectivity for *rac*-**7** was significantly lower than that for *rac*-**1**. From the structural comparison between monomers **1** and **7**, it is concluded that the chirality of the monomer is also essential for the enantiomer-selective polymerization as well as the chiral ligands for ATRP.

Enantiomer-Selectivity Requiring the Cyclization of Bifunctional Monomers. The stereochemistry in bifunctional monomer structures dictates the enantiomeric selectivity. To further investigate the monomer-structural effects on the enantiomer-selectivity, the corresponding racemic monofunctional monomer, *rac*-(*R*,*S*)-2-[(*R*,*S*)-4-benzoyl]pentyl(4-vinylbenzoate) (*rac*-**9**), was prepared (Scheme 3). The ATRP of the monomer **9** results in noncyclized polymers and thus provides information to clarify the cyclization effects on the enantiomer-selective polymerization. The polymerization of *rac*-**9** using the ATRP initiating system consisting of **2**/CuBr/**3** was carried out in anisole at 90 °C ($[rac\text{-}\mathbf{9}]_0 = 0.1$ mol L^{-1} and $[rac\text{-}\mathbf{9}]_0/[\mathbf{2}]_0/[\text{CuBr}]_0/[\mathbf{3}]_0 = 100/1/2/4$). Run 6 in Table 1 shows the result that the polymerization with the 24% monomer conversion produced polymer **10** with the M_n (M_w/M_n) of 8 600 (1.22). However, the recovered monomers showed an equimolar mixture of *RR*-**9** and *SS*-**9** enantiomers, and the resulting noncyclized polymer **10** showed no optical activity at all, demonstrating that the enantiomer-selective polymerization requires cyclization during the ATRP. The result for this control experiment for cyclization is quite consistent with the report by Yu and Ruckenstein, in which the metal catalyst consisting of CuBr/(−)-sparteine lacked any stereochemical control of the resulting poly(methylmethacrylates) and polystyrenes.[25]

Conclusions

The enantiomer-selective radical polymerization was demonstrated for the cyclopolymerization of racemic bifunctional monomer, *rac*-2,4-pentanediyl bis(4-vinylbenzoate) (*rac*-**1**), through the ATRP with methyl 2-bromoisobutylate/CuBr/chiral ligands. From the kinetic study for the homopolymerizations of enantiomerically pure bis(4-vinylbenzoate)s, (2*R*,4*R*)-2,4-pentanediyl bis(4-vinylbenzoate) (*RR*-**1**) and (2*S*,4*S*)-2,4-pentanediyl bis(4-vinylbenzoate) (*SS*-**1**), and their enantiomeric copolymerizations with the ATRP using (−)-sparteine, the reactive ratio of $K_{RR}/K_{SS}/K_{SR}/K_{RS}$ was found to be 2.1/1.0/2.5/1.3. Thus, the chiral initiating system involving (−)-sparteine preferentially reacted the *RR*-**1** into the growing ends with both *RR*-**1** and *SS*-**1** to achieve the enantiomer-selective radical polymerization. As well as the chiral ligand, the cyclopolymerization of the bifunctional monomer was crucial for the enantiomer-selective radical polymerization. The observed enantiomeric selectivity provides the starting point for the stereospecific polymerization mediated through ATRP. Ongoing research is focused on the monomer and catalyst design in order to develop a high level of enantiomer-selectivity.

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Supporting Information Available: Figure showing kinetic plots for the polymerizations of *rac*-**1** using *RR*-**5** and *SS*-**5**, scheme showing four possible scenarios for the polymerization of *rac*-**1** through the ATRP with **3**, figures showing plots of the M_n and M_w/M_n of the polymers obtained through the homopolymerizations of *RR*-**1** and *SS*-**1** as a function of the monomer conversions, table listing the results of the enantiomeric copolymerization of *RR*-**1** and *SS*-**1**, figures showing Kelen−Tüdös plots for the copolymerizations of *RR*-**1** and *SS*-**1**, plots of the M_n and M_w/M_n of **10** as a function of the monomer conversion, and kinetic plots for the polymerization of *rac*-**9**. This material is available free of charge via the Internet at http://pubs.acs.org.

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