SHORT COMMUNICATIONS

Enantiomer-Selective Radical Polymerization of *rac*-2,4-Pentanediyl Dimethacrylate by 2,2′-Azobisisobutyronitrile/Copper(II) Trifluoromethanesulfonate/Chiral Diamine as Asymmetric Reverse Atom Transfer Radical Polymerization Initiating System

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Asymmetric polymerization, such as asymmetric synthesis polymerization, helix-sense selective polymerization, and enantiomer-selective polymerization, is of significant interest from the viewpoint of the precise control of a polymerization system. In general, ionic and coordination polymerization systems were easily modified into chiral ones, so that they were used for preparing various types of asymmetric polymerizations, *e.g.*, high enantiomer-selectivity was achieved for the anionic polymerization of the racemic α-monosubstitued benzyl methacrylate using the (−)-sparteine/Grignard reagent[1−3] and the ring-opening polymerization of propylene sulfide with (−)-binaphthol/ZnEt$_2$.[4,5] Although the radical polymerization is also available for asymmetric polymerization, little is known about the enantiomer-selective radical polymerization.[6,7]

Recently, we reported the enantiomer-selective radical cyclopolymerization of *rac*-2,4-pentanediyl dimethacrylate (*rac*-1) using the atom transfer radical polymerization (ATRP) initiating system modified with chiral ligands, *i.e.*, the methyl 2-bromoisobutyrate/CuBr/chiral amine ligand.[8] Matyjaszewski has expanded the ATRP initiating system into the "reverse" ATRP initiating system such as the 2,2′-azobisisobutyronitrile (AIBN)/copper(II) trifluoromethanesulfonate (Cu(OTf)$_2$)/amine ligand.[9] Therefore the significant interest is to examine the "reverse" ATRP initiating system as a chiral one for the asymmetric polymerization. Here, we report the enantiomer-selective radical cyclopolymerization of *rac*-1 using the AIBN/Cu(OTf)$_2$/chiral diamine

ligand such as 6,6′-bis{(1*R*,4*R*)-hydroxy-1,7,7-trimethylbicyclo[2.2.1]heptan-2-*endo*-yl}-2,2′-bipyridine (**3**), (−)-sparteine (**4**), 3-bis[4′-(*S*)-isopropyloxazoline-2′-yl]pyridine (*S*-**5**), and 3-bis[4′-(*R*)-isopropyloxazoline-2′-yl]pyridine (*R*-**5**) as the asymmetric reverse ATRP initiating system, as shown in Scheme 1.

RESULTS AND DISCUSSION

Table I lists the results for the polymerization of *rac*-1 using the initiating system consisting of AIBN, Cu(OTf)$_2$, and **3**, **4**, *S*-**5**, and *R*-**5** as chiral ligands. All polymerizations homogeneously proceeded to yield gel-free polymers. The characteristic resonance due to the methacrylic groups was not observed in the ^{1}H and ^{13}C NMR spectra of the obtained polymers, indicating that the polymerization of *rac*-1 proceeded through a cyclopolymerization mechanism to afford the polymer essentially consisting of the cyclic repeating units, *i.e.*, the extent of cyclization was *ca.* 100%. The number average molecular weights (M_ns) of the resulting polymers ranged from 47900 to 59100 and the polydispersity indices (M_w/M_ns) were 1.41–2.53.

When **3** and *S*-**5** were used as the chiral ligands, (2*S*,4*S*)-2,4-pentanediyl dimethacrylate (*SS*-**1**) was predominantly polymerized, resulting in the fact that the enantiomeric excess (*e.e.*) of the recovered monomer for **3** was 4.2% for a monomer conversion of 22.8% and that for *S*-**5**, it was 2.3% for a monomer conversion of 18.3%. It should be noted that (2*R*,4*R*)-2,4-pentanediyl dimethacrylate (*RR*-**1**) was predominantly polymerized using 2-bromoisobutyrate/CuBr/**3**
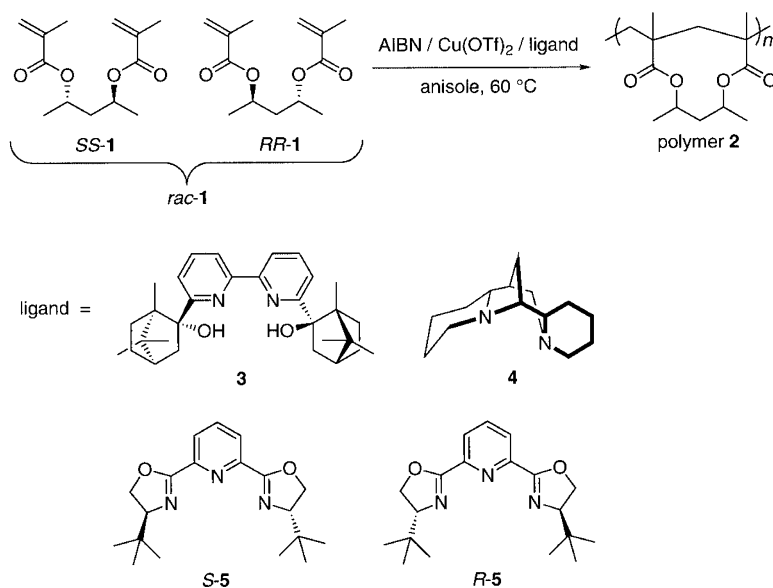
Scheme 1.

Table I. Polymerization of *rac*-**1** using AIBN/Cu(OTf)$_2$/ligand initiation system[a]

| ligand | time hr | conv.[b] % | recovered monomer | | polymer **2** | | r[f] |
			selected monomer	*e.e.*[b,c] %	$M_n(M_w/M_n)$[d]	$[\alpha]_{435}$[e] deg.	
3	0.25	22.8	*SS*-**1**	4.2	47900(2.53)	+13.6	2.0
4	12	18.8	*RR*-**1**	9.4	56300(1.41)	−12.6	1.7
S-**5**	3	18.3	*SS*-**1**	2.3	54500(1.55)	+11.3	1.2
R-**5**	2	18.5	*RR*-**1**	4.6	59100(1.49)	−12.1	1.4

[a]$[rac$-**1**$]_0$ = 0.1 mol L^{-1}; $[rac$-**1**$]_0$/[AIBN]$_0$/[Cu(OTf)$_2$]$_0$/[ligand]$_0$ = 200/1/2/4; solvent, anisole; temperature 60 °C. [b]Determined by HPLC equipped with CHIRALCEL OB-H column. [c]Enantiomeric excess of recovered monomer. [d]Determined by GPC in THF using polystyrene standards. [e]Measured in chloroform (*c* 0.3, 28 °C). [f]Enantiomer selectivity ratio ($r = \ln\{(1$-conv./100)$(1$-*e.e.*/100)$\}/\ln\{(1$-conv./100)$(1+$*e.e.*/100)$\}$)[3].

or *S*-**5** as a normal ATRP initiating system, which was previously reported.[8] The cause of the contradiction in enantiomer-selectivity is obscure, which should be clarified in our near study. On the other hand, *RR*-**1** was preferentially polymerized with 9.4% *e.e.* at a 18.8% monomer conversion and 4.6% *e.e.* at a 18.5% monomer conversion, using **4** and *R*-**5**, respectively. In addition, the enantiomer selectivity apparently changed with the chirality of the ligands used, *e.g.*, the *SS*-**1** enantiomer predominantly polymerized for *S*-**5**, while the *RR*-**1** enantiomer polymerized for *R*-**5**. The resulting polymers exhibited optical activity, and the specific rotations ($[\alpha]_{435}$, *c* 0.3, in chloroform) of the resulting polymers were −12.6° ~ +13.6°, corresponding to the optical activity of the predominantly polymerized enantiomer. These results indicated that the asymmetric reverse ATRP initiating system was effective for the enantiomer-selective radical cyclopolymerization leading to the optically active polymer.

For the polymerization of *rac*-**1** using the AIBN/
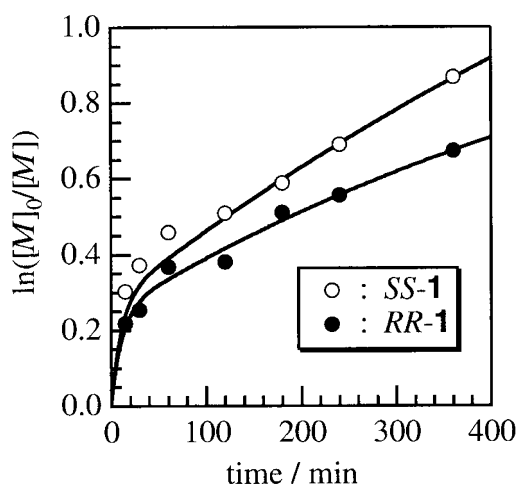
Figure 1. Kinetic plots for the polymerization of *rac*-**1** using AIBN/Cu(OTf)$_2$/**3** initiating system.

Cu(OTf)$_2$/**3** initiating system, the kinetic plots are shown in Figure 1. The reaction rate of the *SS*-**1** enantiomer was larger than that of the *RR*-**1** enantiomer, and
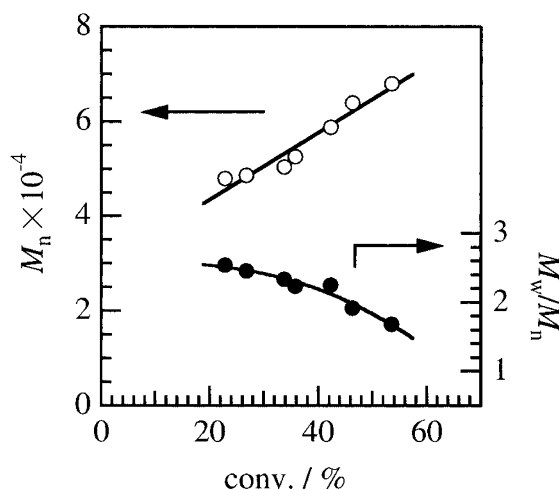
Figure 2. Dependence of M_n and M_w/M_n on monomer conversion for the polymerization of *rac*-**1** using AIBN/Cu(OTf)$_2$/**3** initiating system.
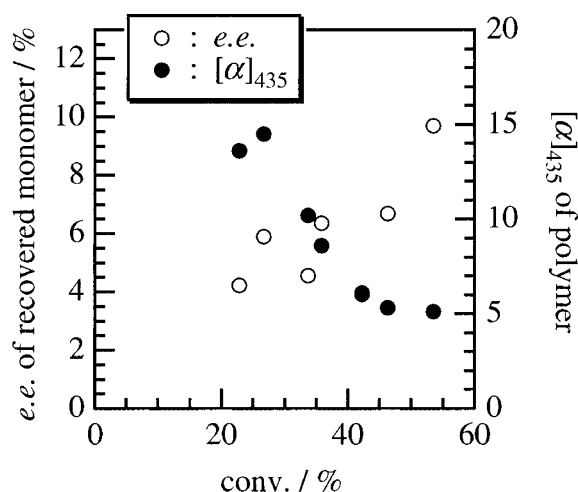

Figure 3. Dependence of *e.e.* of recovered monomer and $[\alpha]_{435}$ of resulting polymer on monomer conversion for the polymerization of *rac*-**1** using AIBN/Cu(OTf)$_2$/**3** initiating system.

the enantiomer selectivity ratio *r* was 2.0 at a 22.8% monomer conversion. Figure 2 shows the relationships between M_n and M_w/M_n *vs.* the monomer conversion. The M_n values of the resulting polymers linearly increased with the monomer conversion, though these values were greater than the calculated ones, *e.g.*, for conversion = 22.8%; the observed and calculated values were 47900 and 10900, respectively. The M_w/M_n values decreased with the increasing monomer conversion. Figure 3 shows the relationships between the *e.e.* value of the recovered monomer and the $[\alpha]_{435}$ value of the resulting polymer *vs.* the monomer conversion. The increasing monomer conversion tended to increase the *e.e.* value of the recovered monomer. On the other hand, the $[\alpha]_{435}$ value of the resulting polymer decreased with the increasing monomer conversion, because the optical purity (*o.p.*) of the polymer decreased with the increase in the monomer conversion, *e.g.*, the *o.p.* value of the resulting polymer was 14.2% at a 22.8% monomer conversion and 2.1% at a 59.6% monomer conversion.[3] These results indicated that the chiral copper complex should affect the addition of *rac*-**1** to the growing end, in which the *SS*-**1** enantiomer was predominantly polymerized, *i.e.*, the enantiomer-selective radical polymerization based on the reverse ATRP.

In summary, we achieved the enantiomer-selective radical polymerization by the cyclopolymerization of *rac*-2,4-pentanediyl dimethacrylate (*rac*-**1**) based on the reverse atom transfer radical polymerization (reverse ATRP) method using chiral initiating systems. For AIBN/Cu(OTf)$_2$/6,6′-bis{(1*R*,4*R*)-hydroxy-1,7,7-trimethylbicyclo[2.2.1]heptan-2-*endo*-yl}-2,2′-bipyridine (**3**), the (2*S*,4*S*)-2,4-pentanediyl dimethacrylate (*SS*-**1**) enantiomer predominantly poly-

merized, and the enantiomeric excess of the recovered monomer increased with the increasing monomer conversion.

EXPERIMENTAL

Materials

2,2′-Azobisisobutyronitrile (AIBN) was recrystallized from methanol. Dry-anisole, 3-bis[4′-(*S*)-isopropyloxazoline-2′-yl]pyridine, 3-bis[4′-(*R*)-isopropyloxazoline-2′-yl]pyridine and trifluoromethanesulfonate (Cu(OTf)$_2$) were purchased from the Aldrich Chem. Co., and used without further purification. (−)-Sparteine was purchased from the Aldrich Chem. Co. and distilled over CaH$_2$ under reduced pressure. 6,6′-Bis{(1*R*,4*R*)-hydroxy-1,7,7-trimethylbicyclo[2.2.1]-heptan-2-*endo*-yl}-2,2′-bipyridine was prepared according to the reported procedure.[10]

Measurements

The ^{1}H and ^{13}C NMR spectra were recorded on a JEOL JNM-400II spectrometer in deutero-chloroform at 25 °C. The optical rotatory measurements were performed in chloroform at 28 °C using a Jasco DIP 1000 digital polarimeter. The molecular weights were measured by gel permeation chromatography (GPC) in THF using a Jasco GPC 900 system equipped with three polystyrene columns (Shodex KF-804L). The number-average molecular weights (M_n) and polydispersity indices (M_w/M_n) were calculated on the basis on a polystyrene calibration. The chiral high-performance liquid chromatography (HPLC) analysis was performed using a Jasco HPLC system (PU-980 Intelligent HPLC pump and UV 975 Intelligent UV detector) equipped with a Daicel CHIRALCEL OB-H column (hexane/2-

propanol (vol. ratio 100/1) as the eluent, flow rate of $0.5\,\mathrm{mL\,min^{-1}}$).

Rac-2,4-Pentanediyl Dimethacrylate

The synthesis of *rac*-2,4-pentanediyl dimethacrylate (*rac*-**1**) was reported in a previous paper.[8]

Polymerization of Rac-1 Using AIBN/Cu(OTf)₂/3

In a glove box (under a moisture- and oxygen-free argon atmosphere, $\mathrm{H_2O}$, $\mathrm{O_2} < 1\,\mathrm{ppm}$), a mixture of *rac*-**1** (500 mg, 2.1 mmol), AIBN (1.7 mg, 1.0×10^{-2} mmol), $\mathrm{Cu(OTf)_2}$ (7.3 mg, 2.1×10^{-2} mmol), **3** (19 mg, 4.2×10^{-2} mmol), and anisole (21 mL) was prepared and 2.0 mL of the mixture was transferred to a dry test tube. The capped test tubes were stirred at 60°C outside the glove box. At the end of the polymerization, a 20 µL aliquot of the reaction mixture was added to hexane (0.5 mL) and filtered through a 0.25 µm pore membrane filter. These samples were analyzed for monomer conversion and enantiomeric excess (*e.e.*) by HPLC equipped with a CHIRALCEL OB-H column, and for M_n and $M_\mathrm{w}/M_\mathrm{n}$ by GPC. The residual polymerization mixtures were passed through a short alumina column to remove the metal salts, and the solvent was removed

under reduced pressure. The residue was poured into hexane and the precipitate was then filtered. The obtained powders were purified by reprecipitation using chloroform-methanol and dried *in vacuo*.

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