Synthesis and catalytic applications of soluble polymer-supported BINOL

Doss Jayaprakash and Hiroaki Sasai*

The Institute of Scientific and Industrial Research, Osaka University, Mihogaoka, Ibaraki, Osaka 567-0047, Japan

Received 10 September 2001; accepted 11 October 2001

Abstract—The synthesis of a soluble polymer containing BINOL residues is described. Titanium-BINOLate and AlLibis(binaphthoxide) catalysts are easily generated from this polymer and applied to the asymmetric reaction of Et_2Zn with benzaldehyde and the asymmetric Michael addition, respectively. The products are obtained in good yields with high enantioselectivities. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Polymer-supported reagents and catalysts have attracted considerable attention as they offer alternative methods to separate and reuse expensive and often toxic chemicals. A variety of chiral ligands have been immobilized in the past and successfully employed in asymmetric hydrogenation,[1] dihydroxylation,[2] epoxidation[3] and Diels–Alder[4] reactions. Among the growing list of ligands being subjected to such a study, chiral 1,1'-bi-2-naphthol[5] (BINOL) has occupied a prominent position in lieu of its ability to form highly enantioselective catalysts with main group elements,[6] transition metals[7] and rare earth elements.[8] A broad spectrum of heterobimetallic complexes containing BINOL that are multifunctional in nature have also been reported.[9] Immobilization of BINOL has earlier been achieved either by grafting onto a sterically irregular polymer backbone[10] or by cross-linking copolymerization.[11] However, the random orientation of ligands and the diffusional limitations encountered in such systems make them less probable candidates for generating catalyst complexes in which two or three BINOL ligands are bound to a central metal ion.[10c] We envisaged that the use of soluble polymer supports might allow the ligands to suitably orient themselves during complexation leading to better catalysts.[12] After completion of the reaction, the polymer-supported catalyst can easily be separated by selective precipitation with solvents such as methanol or hexane. In addition such

systems would have potential applications in membrane reactor technologies.[13] A variety of soluble dendritic BINOL ligands have been recently reported.[14] Herein, we report the synthesis of a soluble polystyrene supported BINOL and its application in asymmetric catalysis.

2. Results and discussion

In the present approach 6-bromo-1,1'-bi-2-naphthol **2** was first synthesized from (R)-1,1'-bi-2-naphthol.[15] Compound **2** was converted to the 6-hydroxymethyl derivative **5** in three steps and subsequently coupled to a styryl derivative by etherification to afford the monomer **6** (Scheme 1). Polymers **8a** [$M_w = 12400$ (PDI = 1.7)][16] and **8b** [$M_w = 9585$ (PDI = 1.4)] were obtained by free radical copolymerization of **6** with an excess of styrene. The protecting groups were finally removed by acid treatment to afford polymers **9a** and **9b**. Both polymers were soluble in solvents such as CH_2Cl_2, toluene and THF and readily precipitated in addition to methanol or hexane.

To test the efficiency of the soluble polymer-supported BINOL as an asymmetric ligand, two reactions were studied: (1) the titanium complex-catalyzed reaction of Et_2Zn with benzaldehyde[17] and (2) the aluminum–lithium complex-catalyzed asymmetric Michael reaction.[18]

Addition of $Ti(O^iPr)_4$ to a solution of **9a** or **9b** in CH_2Cl_2 at room temperature gave an orange solution.

* Corresponding author. Tel.: +81-6-6879-8465; fax: +81-6-6879-8469; e-mail: sasai@sanken.osaka-u.ac.jp
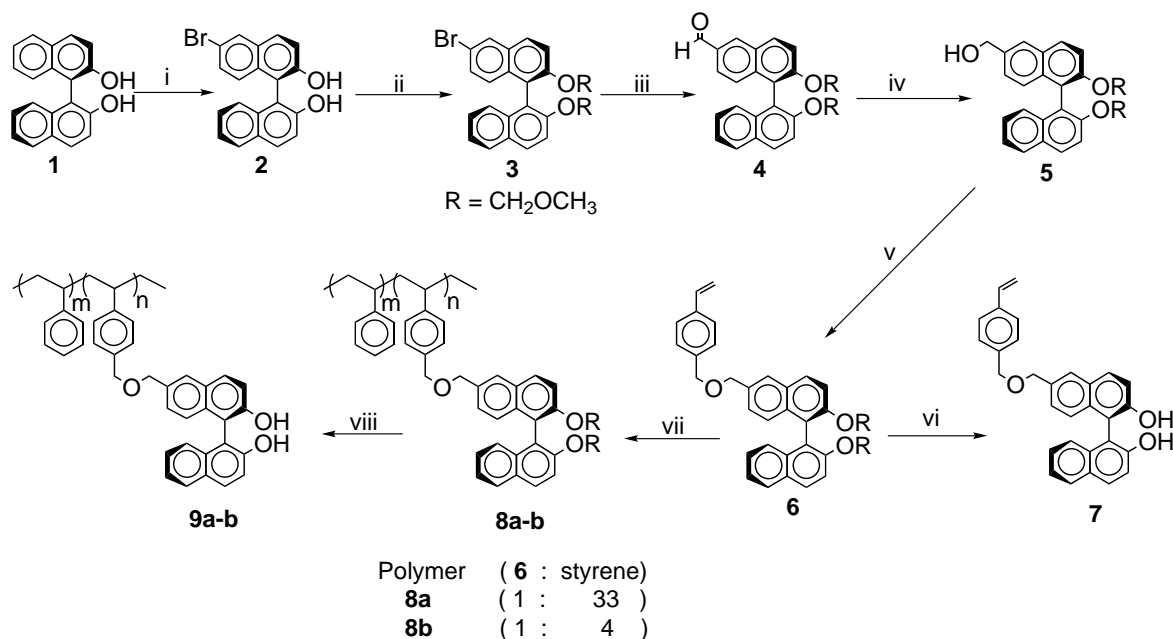
Scheme 1. (i) Br$_2$, CH$_2$Cl$_2$, −78°C, 47%; (ii) NaH, THF, 0°C, 30 min; then CH$_3$OCH$_2$Cl, rt, 3 h, 96%; (iii) *n*-BuLi, THF, −88°C; then DMF, 67%; (iv) NaBH$_4$, THF–MeOH, 0°C, 15 min, 88%; (v) NaH, THF–DMF, 0°C, 30 min; then 4-vinyl-benzylchloride, rt, 72 h, 70%; (vi) HCl, THF, 0°C→rt, 15 h, 92%; (vii) styrene, AIBN, toluene, 75°C, 48 h, 81%; (viii) HCl, THF, 0°C→rt, 15 h.

This solution containing the Ti-BINOLate complex **10a** or **10b** catalyzed the reaction of Et$_2$Zn with benzaldehyde **11** (Table 1). The product alcohol **12** was obtained in moderate yields with good selectivity. CH$_2$Cl$_2$ proved to be a better solvent than toluene in terms of selectivity. Polymeric catalyst **10a** with a lower loading of BINOL afforded the product alcohol in 60% yield with 79% e.e. at −20°C (Table 1, entry 2). Under similar

conditions **10b** afforded the product in 56% yield and 84% e.e. (Table 1, entry 3). The yield and selectivity of the product were found be sensitive to the amount of the catalyst and diethylzinc used. The reaction proceeded faster with the use of 10 mol% of the catalyst at 0°C affording the product in 61% yield and 83% e.e. after 7 h (Table 1, entry 5). When the ratio of diethylzinc was increased to 3 equiv. the product was obtained

Table 1. Asymmetric reaction of diethylzinc with benzaldehyde catalyzed by polymer-supported Ti-BINOLate catalysts
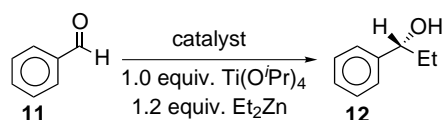
Entry	Catalyst	Solvent	Temp. (°C)	Time (h)	Yield (%)	E.e. (%)[a,b]
1	**10a**	Toluene	−20	14	60	67
2	**10a**	CH$_2$Cl$_2$	−20	15	60	79
3	**10b**	CH$_2$Cl$_2$	−20	22	56	84
4	**10b**	CH$_2$Cl$_2$	Rt	17	42	79
5[c]	**10b**	CH$_2$Cl$_2$	0	7	61	83
6[d]	**10b**	CH$_2$Cl$_2$	0	22	51	80
7	**10b**	Toluene	0	18	44	72
8[e]	**10b**	Toluene	0	20	22	36
9[f]	**10b**	CH$_2$Cl$_2$	0	22	36	79
10[f]	**10b**	CH$_2$Cl$_2$	−20	22	14	76
11[g]	**10b**	Toluene	0	48	–	–

[a] By HPLC Chiralcel-OD column.
[b] The major isomer had the (*R*) configuration.
[c] 10 mol% of the catalyst and 2 equiv. of Et$_2$Zn were used.
[d] 10 mol% of the catalyst and 3 equiv. of Et$_2$Zn were used.
[e] Catalyst was reused after precipitation with hexane.
[f] 20 mol% of the catalyst was used.
[g] Brown solid obtained by concentration of the catalyst solution was used as catalyst.

in 51% yield and 80% e.e. after 22 h at 0°C (Table 1, entry 6). Further increase in the catalyst concentration to 20 mol% resulted in a decrease in the yield and selectivity (Table 1, entry 9). The decrease was more pronounced at −20°C (Table 1, entry 10). No side products were formed under these conditions. Thus, in contrast to the earlier reports,[10d,14g] the use of 10 mol% of the catalyst in the present study resulted in better yields and higher selectivity. Addition of hexane or MeOH to the homogeneous reaction mixture resulted in an orange precipitate. The amount of the precipitated catalyst was found to be much higher than expected, suggesting the co-precipitation of titanium and zinc compounds along with the catalyst. The presence of large amounts of these inseparable side products makes the catalyst insoluble and less effective upon reuse. (Table 1, entry 8). Alternatively, a brown insoluble solid was obtained by concentrating a freshly prepared solution of the catalyst (Table 1, entry 11). This solid also failed to promote the reaction.

To further extend the application of the polymer supported BINOL, immobilization of the AlLibis(binaphthoxide) catalyst (ALB) was attempted. Since this catalyst is comprised of Al, Li and two BINOLs, a direct assembly with BINOL ligands randomly attached to an insoluble, sterically irregular polymer had been less successful. The AlLibis(binaphthoxide) catalyst (ALB) generated with an immobilized linked BINOL resulted in products with moderate selectivity.[10c] Recently we employed soluble and sterically regular polymeric BINOL derivatives to generate poly-ALB catalysts that are highly stereoselective and reusable up to five times.[19] In the present study, the flexibility of the polymer was believed to facilitate the generation of stereoselective ALB catalyst directly by reaction with LiAlH$_4$. A monomeric ALB catalyst **13** was first prepared by the addition of LiAlH$_4$ to an ice cooled solution of **7** in THF.
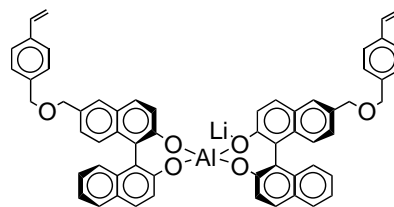

Figure 1. Probable structure of the monomeric catalyst **13**.

The soluble catalyst **13** (Fig. 1) promoted the asymmetric Michael reaction of 2-cyclohexenone **14** with dibenzyl malonate **15** affording the product **16** in 42% yield with 99% e.e. (Table 2, entry 1). This reaction suggested that the loss of C_2 symmetry due to 6-substitution did not have any adverse effect on the selectivity. Subsequently, the polymer-supported ALB catalyst **17** was obtained as an insoluble solid by the addition of LiAlH$_4$ to a THF solution of the **9b** (**Method A**). The solid catalyzed the asymmetric Michael reaction (Table 2, entry 2). The reaction was slow and the product was obtained in 14% yield with 95% e.e. A second-generation catalyst **17-II**[20] obtained by the addition of 9 mol% of *n*-BuLi to the preformed catalyst **17** produced the product in 25% yield with 71% e.e. (Table 2, entry 3). In our earlier study with polymeric ALB catalysts, the yield and the selectivity were found to be influenced by the ratio of LiAlH$_4$ and polymeric BINOL.[18] Interestingly in the present system when an excess of LiAlH$_4$ (2 equiv.) was used to generate the ALB catalyst **18**, the chemical yield increased to 45% with 90% e.e. (Table 2, entry 4). Much better selectivity was obtained when the catalyst was generated by the addition of THF to a mixture of the polymer **9b** and LiAlH$_4$ at 0°C (**Method**

Table 2. Asymmetric Michael reaction catalyzed by polymer supported ALB catalysts
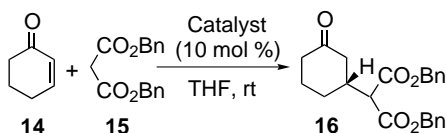
Entry	Catalyst	Method	Time (h)	Yield (%)	E.e. (%)
1	**13**	–	68	42	99
2	**17**	A	96	14	95
3[a]	**17-II**	A	120	25	71
4	**18**	A	48	45	90
5	**18**	B	48	53	95
6[a,b]	**19-II**	B	48	79	81
7	**18**	B	67	68	95
8[c]	**18**	B	89	21	93
9[a]	**18-II**	B	100	72	90
10[c]	**18-II**	B	115	64	45
11[d]	**18**	B	67	59	89

[a] 0.9 molar equiv. of *n*-BuLi was added to form the second-generation catalyst.
[b] 0.05 mmol of dry methanol was added to quench unreacted LiAlH$_4$, if any, before the addition of *n*-BuLi.
[c] Catalyst was reused.
[d] Recovered polymer was used to generate the catalyst.

B, Table 2, entry 5). When 0.05 mmol of MeOH was added to quench any unreacted LiAlH$_4$, before addition of n-BuLi, the resulting catalyst **19-II** afforded the product in 79% yield with 81% e.e. (Table 2, entry 6). Addition of an excess of LiAlH$_4$ could result in catalysts that are structurally different from the originally intended AlLibis(binaphthoxide) complex. Additional support for this hypothesis is given by the fact that the selectivity dropped considerably with the use of the second-generation catalyst **17-II** (Table 2, entry 3). Such a large difference in selectivity was not observed with the second-generation catalyst **18-II** (Table 2, entry 9). In the present study the second-generation catalysts were found to be consistently less selective than their first-generation counterparts. Attempts were made to reuse the catalyst by removing the product solution with a syringe and washing the catalyst repeatedly with THF before the addition of substrates. Under these conditions, use of catalyst **18** led to product in 21% yield with 93% e.e. (Table 2, entry 8). The lower yields obtained on reuse of the first generation catalyst could be attributed to the instability of the catalyst or partial leaching of the metal from the polymer surface. Addition of n-BuLi to restore the activity also resulted in products with lower e.e. (Table 2, entry 10). Nevertheless, the polymer-supported ligand **9b** was recovered along with the product after work up. It was further separated from the product by precipitating into hexane. The precipitated polymer was filtered and dried in vacuo for 3 h at 50°C before reuse. The catalyst **18** generated with the recovered polymer afforded the product in 59% yield with 89% e.e. (Table 2, entry 11).

3. Conclusion

To conclude, a soluble polymer-supported BINOL has been synthesized which could be used to generate Ti-BINOLate and ALB type catalysts. The polymer-supported catalysts were found to be effective in promoting the asymmetric reaction of diethylzinc with benzaldehyde and the asymmetric Michael reaction, respectively. The products were obtained in good yields and with high selectivity. While the catalysts could easily be separated from the products, attempts to reuse them were less successful. In the case of the aluminum complex, the polymer supported BINOL was recovered and reused. Investigations to extend the applications of such polymers to other catalytic systems are currently underway.

4. Experimental

4.1. General

^{1}H and ^{13}C NMR spectra were recorded with JEOL JNM-EX270 FT NMR system. IR spectra were recorded on Shimadzu FTIR 8300. Optical rotations were measured with a Jasco P-1030 polarimeter. HPLC analyses were performed on a Jasco HPLC system (Jasco PU 980 pump and UV-975 UV–vis detector) using a mixture of hexane and i-PrOH as the eluent.

Mass spectra were obtained on a Shimadzu GCMS-QP5050A gas chromatograph mass spectrometer. Molecular weights of the polymers were determined by gel permeation chromatography relative to polystyrene standards using SHODEX GPC KF 803L column.

4.2. Synthesis of (R)-6-bromo-2,2′-dihydroxy-1,1′-binaphalene 2

(R)-1,1′-Dihydroxy-2,2′-binaphthalene (5 g, 17.48 mmol) was dissolved in CH$_2$Cl$_2$ (75 mL) and cooled to −78°C. Bromine (1.2 mL, 8.75 mmol, 0.5 equiv.) was added dropwise over a period of 30 min with constant stirring. After the addition was complete the solution was allowed to warm to room temperature. The excess Br$_2$ was destroyed by the addition of sodium bisulfite. The layers were separated and the organic layer was washed with saturated NaCl solution and dried over anhydrous Na$_2$SO$_4$. Evaporation of the solvent gave the crude product as a pasty solid. Flash column chromatography (SiO$_2$, hexane/ether 4/1) afforded **2** as a colorless foamy solid (2.97 g, 47% yield): $[\alpha]_D^{27}$ −66.9 ($c = 0.45$, CHCl$_3$); IR (Neat) 3419, 1585, 1269, 1072 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 4.97 (s, 1 H), 5.07 (s, 1 H), 6.99 (d, $J = 9.4$ Hz, 1H), 7.07 (d, $J = 8.3$ Hz, 1H), 7.28–7.40 (m, 5H), 7.85–7.90 (m, 2H), 7.95 (d, $J = 9.1$ Hz, 1H), 8.03 (d, $J = 2.0$ Hz, 1H); ^{13}C NMR (CDCl$_3$) δ 110.1, 111.1, 117.7, 118.8, 123.9, 124.0, 126.0, 127.5, 128.3, 129.3, 130.2, 130.3, 130.4, 130.5, 131.5, 131.9, 152.5, 152.8; MS (EI) m/z 366 (M$^+$).

4.3. (R)-6-Bromo-2,2′-bis(methoxymethyloxy)-1,1′-binaphthalene 3

To an ice cooled solution of **2** (2.86 g, 7.87 mmol) in anhydrous THF (25 mL) was added NaH (1.063 g, 26 mmol, 1.5 equiv. as 60% dispersion in oil). The mixture was stirred for 30 min and chloromethylmethylether (2.3 mL, 30 mmol, 3.8 equiv.) was added dropwise. After warming to room temperature the mixture was stirred for a further 3 h then poured into water (100 mL) and the product extracted with ethylacetate. The extract was dried over anhydrous Na$_2$SO$_4$ and concentrated to afford the product. Drying in vacuo for 3 h at 50°C afforded **3** (3.4 g, 96% yield) as a pale yellow solid. $[\alpha]_D^{28}$ +59.1 ($c = 0.45$, CHCl$_3$); IR (Neat) 2898, 2823, 1236, 1145, 1062 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 3.07 (s, 6 H), 4.88 (d, $J = 6.7$ Hz, 2H), 4.99 (d, $J = 3.6$ Hz, 1H), 5.01 (d, $J = 3.6$ Hz, 1H), 6.93 (d, $J = 9.0$ Hz, 1H), 7.00 (d, $J = 7.9$ Hz, 1H), 7.15–7.26 (m, 3H), 7.47 (d, $J = 7.3$ Hz, 1H), 7.50 (d, $J = 7.1$ Hz, 2H), 7.76 (d, $J = 6.1$ Hz, 1H), 7.79 (d, $J = 4.9$ Hz, 1H), 7.86 (d, $J = 9.1$ Hz, 1H), 7.95 (d, $J = 2.0$ Hz, 1H); ^{13}C NMR (CDCl$_3$) δ 55.8, 95.0, 95.1, 117.0, 117.8, 118.1, 123.9, 124.0, 125.1, 126.3, 127.3, 127.8, 128.3, 129.4, 129.5, 129.6, 130.8, 132.4, 133.7, 152.4, 152.8; MS (EI) m/z 454 (M$^+$).

4.4. (R)-6-Formyl-2,2′-bis(methoxymethyloxy)-1,1′-binaphthalene 4

To a solution of **3** (3.3 g, 7.28 mmol) in dry THF was added n-BuLi (6.6 mL, 10.8 mmol, 1.5 equiv. 1.6 M solution in hexane) dropwise at −87°C. The solution

was stirred for 30 min and dry DMF (1.3 mL, 14.6 mmol, 2 equiv.) was slowly added. After being stirred for 2 h the solution was allowed to warm to −20°C. It was then poured into 1N HCl/ice (100 mL). The product was extracted with ethylacetate. The organic layer was washed with saturated NaHCO₃ solution and dried over anhydrous Na₂SO₄. The crude product was obtained upon evaporation of the solvent as a pale yellow oil. Flash column chromatography afforded **4** as a colorless solid (1.95 g, 67% yield): $[\alpha]_D^{28}$ +57.6 (c=0.45, CHCl₃); IR (Neat) 2827, 1689, 1591, 1234, 1145, 1070, 1010, 750 cm^{-1}; ¹H NMR (CDCl₃) δ 3.14 (s, 3H), 3.19 (s, 3H), 4.97 (d, J=6.7 Hz, 1H), 5.03 (d, J=12.9 Hz, 1H), 5.08 (d, J=12.6 Hz, 1H), 5.13 (d, J=7.0 Hz, 1H), 7.08 (d, J=8.0 Hz, 1H), 7.20 (m, 2H), 7.33 (t, J=6.9 Hz, 1H), 7.56 (d, J=9.0 Hz, 1H), 7.67 (d, J=9.1 Hz, 2H), 7.87 (d, J=8.1 Hz, 1H), 7.95 (d, J=9.1 Hz, 1H), 8.10 (d, J=9.0 Hz, 1H), 8.37 (s, 1H), 10.10 (s, 1H); ¹³C NMR (CDCl₃) δ 55.8, 56.0, 94.6, 95.0, 116.8, 117.5, 120.0, 123.1, 124.0, 124.9, 126.4, 127.9, 131.0, 132.4, 134.5, 152.5, 155.2, 191.8; MS (EI) m/z 402 (M⁺).

4.5. (*R*)-6-Hydroxymethyl-2,2′-bis(methoxymethyloxy)-1,1′-binaphthalene 5

To an ice cooled solution of **4** (1.85 g, 4.6 mmol) in THF/MeOH (1:1, 24 mL) was added NaBH₄ (173 mg, 4.6 mmol) and the solution stirred at this temperature for 15 min. The mixture was then poured into water (100 mL) and the product extracted with ethylacetate. After drying over anhydrous Na₂SO₄, the solution was concentrated to afford **5** as a colorless foamy solid (1.63 g, 88%). A portion of the solid was purified by flash column chromatography for analysis. $[\alpha]_D^{29}$ +57.0 (c=0.45, CHCl₃); IR (Neat) 3400, 2823, 1591, 1234, 1145, 1066, 1008, 748 cm^{-1}; ¹H NMR (CDCl₃) δ 3.05 (s, 3H), 3.06 (s, 3H), 4.70 (s, 2H), 4.87 (d, J=6.7 Hz, 2H), 4.96 (d, J=3.3 Hz, 1H), 4.99 (d, J=3.3 Hz, 1H), 7.02–7.17 (m, 4H), 7.23 (t, J=6.7 Hz, 1H), 7.47 (d, J=9.0 Hz, 2H), 7.75 (s, 1H), 7.77 (d, J=8.1 Hz, 1H), 7.82 (d, J=5.4 Hz, 1H), 7.86 (d, J=5.4 Hz, 1H); ¹³C NMR (CDCl₃) δ 55.8, 65.4, 95.1, 95.2, 117.2, 117.4, 121.1, 121.2, 123.9, 125.3, 125.5, 125.6, 125.9, 126.2, 127.7, 129.2, 129.3, 129.6, 129.7, 133.4, 133.8, 136.3, 152.5, 152.6; MS (EI): m/z 404 (M⁺).

4.6. (*R*)-6-(4-Vinylbenzyloxy)methyl-2,2′-bis(methoxymethyloxy)-1,1′-binaphthalene 6

To an ice cooled solution of **5** (1.54 g, 3.81 mmol) in THF/DMF (1:1, 40 mL) was added NaH (135 mg, 5.7 mmol, 1.5 equiv., as 60% purity in oil) and the mixture was stirred at this temperature for 30 min. 4-Vinylbenzylchloride (0.53 mL, 3.84 mmol) was then added dropwise at this temperature and the solution was allowed to warm to room temperature. After stirring for 72 h the mixture was poured carefully into water (100 mL). The product was extracted with ethylacetate, dried over anhydrous Na₂SO₄ and concentrated. Flash column chromatography (SiO₂, hexane/ethylacetate 9/1) afforded **6** as a colorless mass (1.386 g, 70% yield). $[\alpha]_D^{27}$ +43.3 (c=1, CHCl₃); IR (Neat) 2825, 1593, 1236, 1147, 1010 cm^{-1}; ¹H NMR (CDCl₃) δ 3.13 (s, 3H), 3.15 (s, 3H), 4.56 (s, 2H), 4.64 (s, 2H), 4.95 (d, J=6.7 Hz, 1H), 4.96

(d, J=6.7 Hz, 1H), 5.05 (d, 6.7 Hz, 1H), 5.06 (d, 6.7 Hz, 1H), 5.20 (dd, J=10.9, 0.9 Hz, 1H), 5.70 (dd, J=17.6, 0.9 Hz, 1H), 6.65 (dd, J=17.6, 10.9 Hz, 1H), 7.12–7.40 (m, 8H), 7.55 (d, J=9 Hz, 2H), 7.83 (d, J=3.8 Hz, 2H), 7.87 (s, 1H), 7.91 (d, J=3.5 Hz, 1H), 7.94 (d, J=3.4 Hz, 1H); ¹³C NMR (CDCl₃) δ 55.8, 71.8, 72.1, 95.1, 95.2, 113.7, 117.2, 117.4, 121.1, 121.22, 123.9, 125.4, 125.8, 126.1, 126.2, 126.3, 126.5, 127.7, 127.9, 129.2, 129.3, 129.6, 129.7, 133.5, 133.7, 136.4, 136.9, 137.7, 152.5, 152.6; MS (FAB) m/z 521 ([M+H]⁺).

4.7. (*R*)-6-(4-Vinylbenzyloxy)methyl-2,2′-dihydroxy-1,1′-binaphthalene 7

To an ice cooled solution of **6** (250 mg, 3.81 mmol) in THF (2 mL) was added a THF solution of HCl (1 mL conc HCl in 4 mL of THF). The solution was allowed to warm to room temperature slowly. After stirring for 15 h the solution was carefully poured into water (50 mL). The product was extracted with ethylacetate, dried over anhydrous Na₂SO₄ and concentrated. Flash column chromatography (SiO₂, *n*-hexane/ethylacetate 9/1) afforded **7** (190 mg, 92% yield) as a colorless foamy solid. $[\alpha]_D^{28}$ −46.9 (c=0.484, CHCl₃); IR (Neat) 3496, 2854, 1618, 1596, 1141, 1014 cm^{-1}; ¹H NMR (CDCl₃) δ 4.57 (s, 2H), 4.65 (s, 2H), 5.04 (s, 2H), 5.21 (dd, J=10.9, 0.9 Hz, 1H), 5.70 (dd, J=17.6, 0.9 Hz, 1H), 6.65 (dd, J=17.6, 10.9 Hz, 1H), 7.12 (d, J=8.6 Hz), 7.27–7.40 (m, 8H), 7.86 (d, J=3.3 Hz, 1H), 7.87 (s, 1H), 7.94 (d, J=4.5 Hz, 1H), 7.97 (d, J=4.5 Hz, 1H); ¹³C NMR (CDCl₃) δ 71.9, 110.7, 110.8, 113.7, 117.6, 117.9, 123.9, 124.0, 124.4, 126.1, 127.1, 127.4, 127.5, 127.9, 128.3, 129.2, 129.3, 131.2, 131.3, 133.8, 136.4, 137.6, 152.5, 152.6; MS (EI): m/z 432 (M⁺).

4.8. Synthesis of the polymer supported BINOL 8b

To a toluene solution of **6** (0.625 mg in 2 mL) was added AIBN (0.056 g) and styrene (0.55 mL, 4.8 mmol). The solution was purged with argon thoroughly. Polymerization was carried out for 48 h at 75°C. After cooling to room temperature the polymer was first precipitated by addition to methanol followed by hexane. The precipitate was filtered and dried in vacuo at 50°C for 3 h to give the polymer **8b** (0.915 g, 81% yield). $[\alpha]_D^{29}$ +21.1 (c=0.45, CHCl₃); M_w=9585 [Mn=6761, PDI=1.4]; IR (Neat) 2848, 1598, 1238, 1149, 1014 cm^{-1}; ¹H NMR (CDCl₃) δ 0.882 (br), 1.42 (br), 1.82 (br), 3.13 (br), 4.58 (br), 4.97 (br), 5.06 (br), 6.56 (br), 7.15 (br), 7.55 (br), 7.91 (br).

4.9. Removal of the protecting groups in 8b

To an ice cooled solution of the polymer **8b** (880 mg) in THF (2 mL) was added a THF solution of HCl (1 mL conc. HCl in 4 mL of THF). The solution was then allowed to warm to room temperature. After being stirred for 15 h the solution was poured into water (50 mL). The product was extracted with CH₂Cl₂, washed with saturated NaHCO₃ and precipitated into hexane twice. The precipitated polymer **9b** was dried in vacuo at 50°C for 3 h (650 mg). $[\alpha]_D^{29}$ −23.2 (c=0.45, CHCl₃); M_w=9085 [Mn=5345, PDI=1.7]; IR (Neat) 3022,

1598, 1145 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 0.921 (br), 1.10 (br), 1.59 (br), 1.81 (br), 2.17 (br), 4.41 (br), 4.57 (br), 6.56 (br), 7.06 (br), 7.21 (br), 7.33 (br), 7.87 (br).

4.10. Procedure for the asymmetric addition of diethylzinc to benzaldehyde catalyzed by the polymer-supported Ti-BINOLate complex 10b

To a stirred solution of polymer-supported BINOL **9b** (50 mg, 0.05 mmol as a monomer) in CH$_2$Cl$_2$ (2 mL) at room temperature was added dropwise Ti(O^{i}Pr)$_4$ (0.31 ml, 1 mmol). The resulting orange solution **10b** was stirred for 0.5 h and benzaldehyde **11** (0.1 ml, 1 mmol) was added. The solution was cooled to −20°C and diethylzinc (1.2 mL, 1.3 mmol, 1.1 M solution in toluene) was added dropwise. After 22 h the solution was warmed to room temperature and hexane was added to precipitate the catalyst. The precipitate was allowed to settle and the supernatant solution was removed with a syringe. The solution was quenched with 1N HCl and the product was extracted with ethylacetate. The organic layer was washed successively with saturated NaHCO$_3$ solution and brine and dried over anhydrous Na$_2$SO$_4$. Removal of the solvent under reduced pressure gave an oily residue which was purified by flash chromatography (SiO$_2$, n-hexane/ethylacetate 9/1) to give the product **12** (70 mg, 56%) in 84% e.e. as determined by chiral stationary phase HPLC analysis. (DAICEL CHIRALCEL OD column, i-PrOH/n-hexane = 1/19, flow rate 1 mL/min, 7.5 min (major isomer) and 8.4 min (minor isomer).

4.11. Synthesis of polymer supported ALB catalyst 18

4.11.1. Method A. To an iced cooled solution of polymer **9b** (100 mg, 0.1 mmol as a monomer) in THF (1 mL) was added LiAlH$_4$ (3.6 mg, 0.1 mmol). A white precipitate **18** was obtained which was stirred for 30 min and used directly as catalyst for the asymmetric Michael reaction.

4.11.2. Method B. To a mixture of the polymer **9b** (100 mg, 0.1 mmol as a monomer) and LiAlH$_4$ (3.6 mg, 0.1 mmol) at 0°C was added THF (1 mL). The suspension was stirred for 30 min and the resulting white precipitate **18** was used directly as catalyst for the asymmetric Michael reaction.

4.11.3. Catalytic asymmetric Michael reaction. To a stirred suspension of the catalyst **18** were added 2-cyclohexenone **14** (0.05 mL, 0.5 mmol) and dibenzyl malonate **15** (0.125 mL, 0.5 mmol). After stirring for 48 h at room temperature 1N HCl (5 mL) was added. The product mixture was extracted with CH$_2$Cl$_2$ and dried over anhydrous Na$_2$SO$_4$. The solution was concentrated to 2 mL and diluted with hexane (100 mL). The precipitated polymer was filtered and dried (92 mg, 92%). The hexane solution was concentrated and purified by flash column chromatography (SiO$_2$, n-hexane/acetone 10/1) to give the Michael adduct **16**.

The catalyst generated using **Method A** produced the product in 45% yield with 90% e.e., the catalyst gener-ated by **Method B** produced the product in 53% yield with 95% e.e.

The enantiomeric excess was determined by chiral stationary phase HPLC analysis. (DAICEL CHIRAL-PAK AS column, i-PrOH/n-hexane = 1/4, flow rate 1 mL/min, 19.7 min (major isomer) and 25.5 min (minor isomer).

4.11.4. Reuse of the polymer. The recovered polymer was dried in vacuo for 3 h at 45°C. The Michael addition catalyst **18** was generated by Method B. The catalyst afforded the product in 59% yield with 89% e.e.

References

1. Dumont, W.; Poulin, J. C.; Dang, T. P.; Kagan, H. B. *J. Am. Chem. Soc.* **1973**, *95*, 295.
2. (a) Kim, B. M.; Sharpless, K. B. *Tetrahedron Lett.* **1990**, *31*, 3003; (b) Han, H.; Janda, K. D. *J. Am. Chem. Soc.* **1996**, *118*, 7632.
3. Minutolo, F.; Pini, D.; Salvadori, P. *Tetrahedron Lett.* **1996**, *37*, 3375.
4. Hu, Q. S.; Pu, L. *Polym. Prep.* **2000**, *41*, 16.
5. Noyori, R.; Tomino, I.; Tanimoto, Y. *J. Am. Chem. Soc.* **1979**, *101*, 3129.
6. Yamamoto, H.; Yanagisawa, A.; Ishihara, K.; Saito, S. *Pure Appl. Chem.* **1998**, *70*, 1507.
7. Roshini, C.; Franzini, L.; Raffaeli, A.; Salvadori, P. *Synthesis* **1992**, 503.
8. Qian, C.; Zhu, C.; Huang, T. *J. Chem. Soc., Perkin Trans. 1* **1998**, 2131.
9. Shibasaki, M.; Sasai, H.; Arai, T. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1237.
10. (a) Kobayashi, S.; Kusakabe, K.; Ishitani, H. *Org. Lett.* **2000**, *2*, 1225; (b) Lipshutz, B.; Shin, Y.-J. *Tetrahedron Lett.* **2000**, *41*, 9515; (c) Matsunaga, S.; Ohshima, T.; Shibasaki, M. *Tetrahedron Lett.* **2000**, *41*, 8473; (d) Yang, X.; Su, W.; Liu, D.; Wang, H.; Shen, J.; Da, C.; Wang, R.; Chan, A. S. C. *Tetrahedron* **2000**, *56*, 3511.
11. Sellner, H.; Faber, C.; Rheiner, P. B.; Seebach, D. *Chem. Eur. J.* **2000**, *6*, 3692.
12. For a review on soluble polymer supported catalysts, see: (a) Wentworth, H. P., Jr.; Janda, K. D. *Chem. Commun.* **1999**, 1917; (b) Pu. L. *Chem. Eur. J.* **1999**, *5*, 2227.
13. Giffels, G.; Beliczey, J.; Felder, M.; Kragl, U. *Tetrahedron: Asymmetry* **1998**, *9*, 691.
14. (a) Yamago, S.; Furukawa, M.; Azuma, A.; Yoshida, J.-I. *Tetrahedron Lett.* **1998**, *39*, 3783; (b) Brunner, H.; Stefaniak, S.; Zabel, M. *Synthesis* **1999**, 1776; (c) Rheiner, P. B.; Seebach, D. *Chem. Eur. J.* **1999**, *5*, 3221;

(d) Hu, Q.-S.; Pugh, V.; Sabat, M.; Pu, L. *J. Org. Chem.* **1999**, *64*, 7528; (e) Köllner, C.; Pugin, B.; Togni, A. *J. Am. Chem. Soc.* **1998**, *120*, 10274; (f) Schneider, R.; Köllner, C.; Weber, I.; Togni, A. *Chem. Commun.* **1999**, 2415; (g) Fan, Q.-H.; Liu, G.-H; Chen, X.-M.; Deng, G.-J.; Chan, A. S. C. *Tetrahedron: Asymmetry* **2001**, *12*, 1559.

15. 6-Bromo-1,1′-bi-2-naphthol can also be purchased from Kankyo Kagaku Center, Japan.

16. The molecular weights of the polymers were determined by gel-permeation chromatography relative to polystyrene standards.

17. (a) Zhang, F.-Y.; Yip, C.-W.; Cao, R.; Chan, A. S. C. *Tetrahedron: Asymmetry* **1997**, *8*, 585; (b) Mori, M.; Nakai, T. *Tetrahedron Lett.* **1997**, *38*, 6233.

18. Arai, T.; Sasai, H.; Aoe, K.; Date, T.; Shibasaki, M. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 104.

19. Arai, T.; Hu, Q.-S.; Zheng, X.-F.; Pu, L.; Sasai, H. *Org. Lett.* **2000**, *2*, 4261.

20. (a) Arai, T.; Yamada, Y. M. A.; Yamamoto, N.; Sasai, H.; Shibasaki, M. *Chem. Eur. J.* **1996**, *2*, 1368; (b) Arai, T.; Sasai, H.; Yamaguchi, K.; Shibasaki, M. *J. Am. Chem. Soc.* **1998**, *120*, 441.