Catalytic Enantioselective Aryl Transfer to Aldehydes Using Chiral 2,2’-Bispyrrolidine-Based Salan Ligands

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Received: 24 December 2010; in revised form: 15 March 2011 / Accepted: 16 March 2011 / Published: 6 April 2011

Abstract: Chiral C₂-symmetric diamines have emerged as versatile auxiliaries or ligands in numerous asymmetric transformations. Chiral 2,2’-bispyrrolidine-based salan ligands were prepared and applied to the asymmetric aryl transfer to aldehydes with arylboronic acids as the source of transferable aryl groups. The corresponding diarylmethanols were obtained in high yields with moderate to good enantioselectivities of up to 83% ee.

Keywords: 2,2’-bispyrrolidine; salan ligands; aryl transfer; arylboronic acid; enantioselectivity

1. Introduction

Chiral diarylmethanols are important intermediates and precursors for the synthesis of pharmacologically and biologically active compounds [1-8]. Therefore, the development of effective catalyst systems for the synthesis of these compounds is of significant importance for organic chemists. The scientifically important protocols for the synthesis of chiral diarylmethanols commonly
involve two strategies: (1) the asymmetric reduction of prochiral diaryl ketones [9-13], (2) the enantioselective aryl transfer to aromatic aldehydes [14-16]. The reduction method requires an ortho substituent on one of the aryls or electronic different aryl groups for optimum results. The second method seems easy to realize chiral induction due to the large steric and electronic differences between an aryl group and a hydrogen atom on the aldehyde substrates with diphenylzinc. As reported previously, many functionalized diarylzincs used as the transferring nucleophiles are unstable and difficult to synthesize, so the method of the aryl transfer to aldehyde is greatly limited. Recently, an elegant method that the arylzinc species prepared in situ by transmetalation between organoboron [17-19] or organoboronic derivatives [20-26] and diethylzinc has been proposed as an alternative for the synthesis of salt-free organozinc reagents. We have also successfully developed an efficient and practical method for the synthesis of diarylmethanols by transmetalation using the arylboronic acid in the presence of trimethylgallium [27]. These methods allow the exploitation of a broad range of substituted aryl transfer reagents since numerous arylboronic acids are commercially available, and a lot of excellent ligands were developed and applied to the asymmetric aryl transfer reaction with good results [28-41]. For the future, the introduction of the new, effective and more easily available catalysts is also a field of continuous interest for the catalytic aryl transfer reaction.

Chiral C$_2$-symmetric diamines have emerged as versatile auxiliaries or ligands in numerous asymmetric transformations [42-44]. (R,R)-2,2'-bispyrrolidine, initially developed by Hirama, was synthesized by various routes [45-50], and its derivatives had been successfully employed as chiral ligands or organocatalysts in many asymmetric reactions [51-59]. So far, the application of 2,2'-bispyrrolidine-based salan ligands [60,61] in asymmetric catalysis has not been reported. We describe herein our efforts toward the synthesis of optically active diarylmethanols through the asymmetric aryl transfer to aldehydes under the catalysis of (R,R)-2,2'-bispyrrolidine-based salan ligands.

Figure 1. Structures of Ligands L1-L6.

2. Results and Discussion

A preliminary study was performed to test the catalytic property of the ligands L1-L6 (Figure 1) in the asymmetric phenyl transfer reaction to 4-nitrobenzaldehyde at 0 °C. As is evident from Table 1, the resulting products could be obtained in moderate yield, but low enantioselectivity when (1R,2R)-cyclohexane-1,2-diamine-based ligands L1-L4 were tested (Table 1, entries 1-4). Gratifyingly, we found that the ligands L5 and L6 were more effective in this reaction (Table 1, entries 5-6). The ee
value of the product could be increased to 63% when the reaction was carried out at −25 °C (Table 1, entry 7). Increasing catalyst loading had a positive impact on both the yield and enantioselectivity. The best result was obtained in 88% yield with 83% ee while using 20 mol% of L6 (Table 1, entry 9).

Table 1. Asymmetric Phenyl Transfer to 4-nitrobenzaldehyde. 

| Entry | Ligand | Mol% | T(°C) | Yield(%) | Ee(%) |
|-------|--------|------|-------|----------|-------|
| 1     | L1     | 10   | 0     | 66       | 6     |
| 2     | L2     | 10   | 0     | 73       | 11    |
| 3     | L3     | 10   | 0     | 69       | 16    |
| 4     | L4     | 10   | 0     | 80       | 3     |
| 5     | L5     | 10   | 0     | 74       | 31    |
| 6     | L6     | 10   | 0     | 84       | 43    |
| 7     | L6     | 10   | -25   | 70       | 63    |
| 8     | L6     | 15   | -25   | 80       | 71    |
| 9     | L6     | 20   | -25   | 88       | 83(S) |

All the reactions were carried out on 0.2 mmol scale of substrates with 2 equiv of arylboronic acid and 6 equiv of Et₂Zn in toluene for 24 h. Isolated yields. Determined by HPLC with a Chiralcel OB-H column. The absolute configuration of the products were determined by comparison with literature values.

After having established the optimal protocol for the asymmetric phenyl transfer reaction, we further extended the reaction to a series of aldehyde substrates (Table 2). The electronic properties of the aromatic rings of the aldehydes have a significant influence on the enantioselectivity in this reaction. The aldehydes with electron-withdrawing substituents provided better results than those with electron-donating substituents in terms of ee values. 4-Nitrobenzaldehyde gave the corresponding diarylmethanol with 83% ee, but 4-methoxybenzaldehyde only with 11% ee (Table 2, entries 1, 2 and 10). Similar results were obtained when 3-substituted-benzoaldehydes (Table 2, entries 3 and 9) or 2-substituted-benzaldehydes (Table 2, entries 5, 6 and 8) were tested. However, an exception was observed for 2-nitrobenzaldehyde (Table 2, entry 4), presumably caused by the chelating effect of the NO₂ group with the lewis acids [62,63]. The enantioselectivity was also found to be influenced by the steric effect with the same exception of 2-nitrobenzaldehyde. ortho-Substituted (-Cl or -Me) benzaldehydes gave higher ee values (Table 2, entries 6 vs 2 or 8 vs 9). It should be noted that the reaction of 2-naphthaldehyde proceeded well, giving 70% ee and good yield (Table 2, entry 11), and α,β-unsaturated cinnamaldehyde gave the corresponding product with only moderate enantioselectivity (Table 2, entry 12).

We also further investigated the asymmetric aryl transfer to aromatic aldehydes with substituted phenylboronic acids. As shown in Table 3, when 4-chlorophenylboronic acid was chosen as the aryl source and 4-nitrobenzaldehyde as the substrate, 71% ee was obtained (Table 3, entry 1). And 54% ee was obtained when 4-methoxylphenylboronic acid was tested (Table 3, entry 3).
Table 2. Asymmetric Phenyl Transfer to Aromatic Aldehydes. $^a$

| Entry | Ar        | Product | Yield (%)$^b$ | Ee (%)$^c$ |
|-------|-----------|---------|---------------|------------|
| 1     | 4-NO$_2$C$_6$H$_4$ | 3a      | 88            | 83(S)      |
| 2     | 4-ClC$_6$H$_4$    | 3b      | 80            | 41(S)      |
| 3     | 3-NO$_2$C$_6$H$_4$| 3c      | 91            | 75(S)      |
| 4     | 2-NO$_2$C$_6$H$_4$| 3d      | 85            | 41(R)      |
| 5     | 2-CF$_3$C$_6$H$_4$| 3e      | 72            | 80(R)      |
| 6     | 2-ClC$_6$H$_4$    | 3f      | 84            | 73(S)      |
| 7     | 3-BrC$_6$H$_4$    | 3g      | 85            | 26(S)      |
| 8     | 2-MeC$_6$H$_4$    | 3h      | 76            | 60(S)      |
| 9     | 3-MeC$_6$H$_4$    | 3i      | 78            | 52(S)      |
| 10    | 4-MeOC$_6$H$_4$   | 3j      | 80            | 11(S)      |
| 11    | 2-C$_{10}$H$_7$   | 3k      | 80            | 70(S)      |
| 12    | PhCH=CH          | 3l      | 76            | 47(R)      |

$^a$All reactions were carried out on 0.15 mmol scale of substrates with 2 equiv of arylboronic acid and 6 equiv of Et$_2$Zn in toluene at −25 °C for 24 h in the presence of 20 mol% ligand; $^b$ Isolated yields; $^c$ Enantiomeric excess was determined by HPLC with a Chiralcel OB-H, OD-H or AD-H column; $^d$ The absolute configuration of the products were determined by comparison with literature values.

Table 3. Asymmetric Aryl Transfer to Aldehydes. $^a$

| Entry | Ar$^1$ | Ar$^2$ | Product | Yield (%)$^b$ | Ee (%)$^c$ |
|-------|--------|--------|---------|---------------|------------|
| 1     | 4-ClC$_6$H$_4$ | 4-NO$_2$C$_6$H$_4$ | 4a      | 75            | 71         |
| 2     | 4-ClC$_6$H$_4$ | 3-BrC$_6$H$_4$    | 4b      | 82            | 55         |
| 3     | 4-MeOC$_6$H$_4$| 4-NO$_2$C$_6$H$_4$| 4c      | 78            | 54(S)$^d$  |
| 4     | 4-MeOC$_6$H$_4$| 3-NO$_2$C$_6$H$_4$| 4d      | 70            | 24         |
| 5     | 3,5-diMeC$_6$H$_3$| C$_6$H$_6$ | 4e      | 70            | 48         |

$^a$All reactions were carried out on 0.15 mmol scale of substrates with 2 equiv of arylboronic acid and 6 equiv of Et$_2$Zn in toluene at −25 °C for 24 h in the presence of 20 mol% ligand; $^b$ Isolated yields; $^c$ Enantiomeric excess was determined by HPLC with a Chiralcel OB-H, OD-H or AD-H column; $^d$ The absolute configuration of the products were determined by comparison with literature values.

3. Experimental

3.1. General

All reactions were carried out under an argon atmosphere using standard Schlenk techniques. Solvents were dried and distilled prior to use according to standard methods. Unless otherwise indicated, all materials were obtained from commercial sources and liquid aldehydes were freshly distilled before use. For thin-layer chromatography (TLC), compounds were visualized by irradiation with UV light on GF 254 silica gel plates. $^1$H-NMR and $^{13}$C-NMR spectra were recorded in CDCl$_3$ on a Bruker ARX-300 spectrometer with chemical shifts being referenced to SiMe$_4$ used as internal
standard. The coupling constants $J$ are given in Hz. HPLC analysis were performed on a chiral column (Daicel Chiralcel OB-H, OD-H or AD-H column) on a Chromatography Interface 600 Series Link instrument and Series 200 pump), with Series 200 UV/VIS detection at 254 nm. The solvent system used has hexane (A)-2-propanol (B) in the indicated proportions. Optical rotations were measured on Rudolph Research Analytical Autopol III Automatic Polarimeter equipped with a 100 mm cell. Mass spectra (EI-MS) were taken using a Shimadzu GCMS-QP2010 mass spectrometer. High Resolution Mass Spectra (HRMS) were taken using a LTQ Orbitrap XL ThermoFisher unit.

3.2. Typical Procedure for the Asymmetric Aryl Transfer Reaction

In a 20 mL flame-dried Schlenk reaction tube, diethylzinc (0.9 mmol, 6 equiv, 1.5 M in toluene solution) was added dropwise to a solution of phenylboronic acid (0.3 mmol, 2 equiv) in toluene (3 mL) under an argon atmosphere. After stirring for 12 h at 60 °C, a toluene solution of L6 (20 mol%) was introduced. The reaction was stirred for an additional 30 minutes and cooled to −25 °C followed by the addition of aldehydes (0.15 mmol). After completion of the reaction (monitored by TLC), the reaction solution was quenched with saturated aqueous NH$_4$Cl (3 mL) and further extracted with ethyl acetate (3 × 5 mL). The combined organic layer was dried over Na$_2$SO$_4$. Evaporation of the solvent gave the crude product, which was further purified by preparative TLC to afford the corresponding chiral diarylmethanols.

**3a.** (S)-4-Nitrophenyl(phenyl)methanol. $^1$H-NMR: δ 8.19 (d, $J = 7.2$ Hz, 2H), 7.58 (d, $J = 7.2$ Hz, 2H), 7.37–7.33 (m, 5H), 5.92 (s, 1H), 2.25 (brs, 1H). 83% ee determined by HPLC with a Chiralcel OB-H column (A/B = 70:30, 0.8 mL/min, uv 230 nm): $t_R = 21.05$ min (minor), $t_R = 35.74$ min (major). $[^\alpha]_D^{23} = +31.6$ (c = 0.50, EtOH).

**3b.** (S)-4-Chlorophenyl(phenyl)methanol. $^1$H-NMR: δ 7.38–7.33 (m, 4H), 7.31–7.27 (m, 5H), 5.80 (s, 1H), 2.20 (brs, 1H). 41% ee determined by HPLC with a Chiralcel OB-H column (A/B = 90:10, 1.0 mL/min, uv 230 nm): $t_R = 10.21$ min (minor), $t_R = 18.33$ min (major). $[^\alpha]_D^{23} = +5.9$ (c = 0.64, EtOH).

**3c.** (S)-3-Nitrophenyl(phenyl)methanol. $^1$H-NMR: δ 8.30 (s, 1H), 8.11 (d, $J = 8.1$ Hz, 1H), 7.72 (d, $J = 7.8$ Hz, 1H), 7.50 (t, $J = 7.8$ Hz, 1H), 7.40–7.29 (m, 5H), 5.92 (s, 1H), 2.13 (brs, 1H). 75% ee determined by HPLC with a Chiralcel OB-H column (A/B = 80:20, 0.8 mL/min, uv 230 nm): $t_R = 34.19$ min (minor), $t_R = 47.40$ min (major). $[^\alpha]_D^{23} = +42.5$ (c = 0.40, EtOH).

**3d.** (R)-2-Nitrophenyl(phenyl)methanol. $^1$H-NMR: δ 7.94 (dd, $J = 7.8$, 1.5 Hz, 1H), 7.75 (dd, $J = 7.8$, 1.5 Hz, 1H), 7.64 (dt, $J = 7.5$, 1.2 Hz, 1H), 7.46 (t, $J = 7.8$, 1.5 Hz, 1H), 7.36–7.29 (m, 5H), 6.44 (s, 1H), 2.02 (brs, 1H). 41% ee determined by HPLC with a Chiralpak AD-H column (A/B = 90:10, 0.8 mL/min, uv 254 nm): $t_R = 13.57$ min (major), $t_R = 14.62$ min (minor); $[^\alpha]_D^{23} = 11.2$ (c = 0.32, EtOH).
(R)-2-Trifluoromethylphenyl(phenyl)methanol (3e). 1H-NMR: δ 7.66 (t, J = 7.8 Hz, 2H), 7.55 (t, J = 7.8 Hz, 1H), 7.42–7.32 (m, 5H), 7.30–7.27 (m, 1H), 6.32 (s, 1H), 1.99 (brs, 1H). 80% ee determined by HPLC with a Chiralcel OD-H column (A/B = 90:10, 0.5 mL/min, uv 254 nm): tR = 9.33 min (major), tR = 11.79 min (minor). [α]D20 = −37.2 (c = 0.5, EtOH).

(S)-2-Chlorophenyl(phenyl)methanol (3f). 1H-NMR: δ 7.60 (d, J = 7.8 Hz, 1H), 7.42–7.39 (m, 2H), 7.36–7.28 (m, 5H), 7.25–7.22 (m, 1H), 6.24 (s, 1H), 2.05 (brs, 1H). 73% ee determined by HPLC with a Chiralcel OB-H column (A/B = 90:10, 1.0 mL/min, uv 230 nm): tR = 8.97 min (minor), tR = 10.00 min (major). [α]D20 = −20.6 (c = 0.64, EtOH).

(S)-3-Bromophenyl(phenyl)methanol (3g). 1H-NMR: δ 7.57 (s, 1H), 7.42–7.35 (m, 5H), 7.33–7.27 (m, 2H), 7.20 (t, J = 7.8 Hz, 1H), 5.78 (s, 1H), 2.33 (brs, 1H). 26% ee determined by HPLC with a Chiralcel OB-H column (A/B = 90:10, 1.0 mL/min, uv 230 nm): tR = 15.17 min (minor), tR = 27.81 min (major). [α]D20 = +11.4 (c = 0.76, EtOH).

(S)-2-Methylphenyl(phenyl)methanol (3h). 1H-NMR: δ 7.53 (d, J = 9.0 Hz, 1H), 7.34–7.21(m, 7H), 7.16 (t, J = 8.1 Hz, 1H), 6.02 (s, 1H), 2.26 (s, 3H), 1.95 (s, 1H). 60% ee determined by HPLC with a Chiralcel OB-H column (A/B = 90:10, 1.0 mL/min, uv 230 nm): tR = 9.47 min (minor), tR = 10.6 min (major). [α]D20 = −19.3 (c = 0.30, EtOH).

(S)-3-Methylphenyl(phenyl)methanol (3i). 1H-NMR: δ 7.41–7.34 (m, 4H), 7.30–7.27 (m, 2H), 7.24–7.16 (m, 2H), 7.09 (d, J = 7.5 Hz, 1H), 5.81 (s, 1H), 2.35 (s, 3H), 2.02 (brs, 1H). 52% ee determined by HPLC with a Chiralcel OB-H column (A/B = 90:10, 1.0 mL/min, uv 230 nm): tR = 12.39 min (minor), tR = 21.34 min (major). [α]D20 = −15.8 (c = 0.34, EtOH).

(S)-4-Methoxyphenyl(phenyl)methanol (3j). 1H-NMR: δ 7.37–7.34 (m, 3H), 7.30–7.26 (m, 4H), 6.88 (d, J = 9.0 Hz, 2H), 5.81 (s, 1H), 3.78 (s, 3H), 2.23 (brs, 1H). 11% ee determined by HPLC with a Chiralcel OB-H column (A/B = 90:10, 1.0 mL/min, uv 230 nm): tR = 21.79 min (minor), tR = 24.03 min (major). [α]D20 = 8.1 (c = 0.42, EtOH).

(S)-2-Naphathyl(phenyl)methanol (3k). 1H-NMR: δ 7.90 (s, 1H), 7.86–7.79 (m, 3H), 7.50–7.42 (m, 5H), 7.38–7.28 (m, 3H), 6.01 (s, 1H), 2.06 (brs, 1H). 70% ee determined by HPLC with a Chiralcel OD-H column (A/B = 85:15, 0.8 mL/min, uv 230 nm): tR = 12.71 min (major), tR = 15.08 min (minor). [α]D20 = −18.4 (c = 0.46, EtOH).

(R)-1, 3-Diphenylprop-2-en-1-ol (3l). 1H-NMR: δ 7.47–7.33 (m, 5H), 7.32–7.27 (m, 3H), 7.29–7.24 (m, 2H), 6.70 (d, J = 15.6 Hz, 1H), 6.40 (dd, J = 6.3, 15.6 Hz, 1H), 5.40 (d, J = 6.6 Hz, 1H), 2.15 (brs, 1H). 47% ee determined by HPLC with a Chiralcel OD-H column (A/B = 80:20, 0.8 mL/min, uv 254 nm): tR = 9.31 min (minor), tR = 11.14 min (major). [α]D20 = +13.5 (c = 0.40, EtOH).

4-Chlorophenyl(4-nitrophenyl)methanol (4a). 1H-NMR: δ 8.20 (d, J = 8.7 Hz, 2H), 7.55 (d, J = 8.7 Hz, 2H), 7.36–7.27 (m, 4H), 5.90 (s, 1H), 2.04 (brs, H). 71% ee determined by HPLC with a Chiralcel OB-
H column (A/B = 80:20, 0.8 mL/min, uv 230 nm): t_R = 22.92 min (minor), t_R = 25.07 min (major). \([\alpha]_D^{23} = -19.5 (c = 0.64, \text{EtOH}).\)

4-Chlorophenyl(3-bromophenyl)methanol (4b). \(^1\)H-NMR: \(\delta\) 7.53 (s, 1H), 7.41 (d, \(J = 7.5\) Hz, 1H), 7.39–7.28 (m, 4H), 7.25–7.24 (m, 2H), 7.20 (t, \(J = 7.5\) Hz, 1H), 5.77 (s, 1H), 2.04 (brs, 2H). 55% ee determined by HPLC with a Chiralcel OD-H column (A/B = 85:15, 0.8 mL/min, uv 230 nm): t_R = 7.80 min (major), t_R = 8.58 min (minor). \([\alpha]_D^{23} = +22.8 (c = 0.60, \text{EtOH}).\)

(S)-4-Methoxylphenyl(4-nitrophenyl)methanol (4c). \(^1\)H-NMR: \(\delta\) 8.19 (d, \(J = 8.7\) Hz, 2H), 7.57 (d, \(J = 8.4\) Hz, 2H), 7.25 (d, \(J = 8.5\) Hz, 2H), 6.89 (d, \(J = 8.7\) Hz, 2H), 5.88 (s, 1H), 5.78 (s, 1H), 3.80 (s, 3H), 2.20 (s, 1H). 54% ee determined by HPLC with a Chiralpak AD-H column (A/B = 85:15, 0.8 mL/min, uv 254 nm): t_R = 15.60 min (minor), t_R = 19.25 min (major). \([\alpha]_D^{23} = +27.9 (c = 0.44, \text{EtOH}).\)

4-Methoxylphenyl(3-nitrophenyl)methanol (4d). \(^1\)H-NMR: \(\delta\) 8.28 (s, 1H), 8.10 (d, \(J = 8.1\) Hz, 1H), 7.71 (d, \(J = 8.1\) Hz, 1H), 7.49 (t, \(J = 8.1\) Hz, 1H), 7.27 (d, \(J = 6.6\) Hz, 2H), 6.80 (d, \(J = 6.9\) Hz, 2H), 5.88 (s, 1H), 3.80 (s, 3H), 2.28 (brs, 1H). 24% ee determined by HPLC with a Chiralcel OD-H column (A/B = 85:15, 0.8 mL/min, uv 230 nm): t_R = 15.08 min (major), t_R = 16.23 min (minor). \([\alpha]_D^{23} = +23.8 (c = 0.50, \text{EtOH}).\)

3, 5-Dimethylphenyl(phenyl)methanol (4e). \(^1\)H-NMR: \(\delta\) 7.42–7.28 (m, 5H), 7.01 (s, 2H), 6.93 (s, 1H), 5.77 (s, 1H), 2.31 (s, 6H), 2.18 (brs, 1H). 48% ee determined by HPLC with a Chiralcel OD-H column (A/B = 90:10, 0.8 mL/min, uv 254 nm): t_R = 8.67 min (minor), t_R = 9.58 min (major). \([\alpha]_D^{23} = +20.4 (c = 0.65, \text{EtOH}).\)

4. Conclusions

In summary, we have reported the asymmetric aryl transfer to aldehydes with aryloboronic acids as aryl sources in the presence of the chiral 2,2′-bispyrrolidine-based ligand L6. The corresponding diarylmethanols could be obtained in high yields with moderate to good enantioselectivities. Further work on the asymmetric addition mechanism and the broad application of chiral 2,2′-bispyrrolidine-based ligands in other asymmetric catalytic reactions are now in progress in our laboratory.

Acknowledgements

We gratefully acknowledge the National Natural Science Foundation of China (20832001, 20972065, 21074054) and the National Basic Research Program of China (2007CB925103, 2010CB923303) for their financial support. The Major Scientific and Technological Special Project (2009ZX09103-081) is also acknowledged.

References and Notes

1. Shafi’ee, A.; Hite, G. Absolute configurations of the pheniramines, methyl phenidates, and pipradrals. J. Med. Chem. 1969, 12, 266-270.
2. Ebnöther, A.; Weber, H.P. Synthesis and absolute configuration of clemastine and its isomers. Helv. Chim. Acta 1976, 59, 2462-2468.
3. Meguro, K.; Aizawa, M.; Sohda, T.; Kawamatsu, A.; Nagaoka, A. New 1,4-dihydropyridine derivatives with potent and long-lasting hypotensive effect. Chem. Pharm. Bull. 1985, 33, 3787-3797.
4. Toda, F.; Tanaka, K.; Koshiro, K. A new preparative method for optically active diarylcarbinols. Tetrahedron Asymmetry 1991, 2, 873-874.
5. Casy, A.F.; Drake, A.F.; Ganellin, C.R.; Mercer, A.D.; Upton, C. Stereochemical studies of chiral H-1 antagonists of histamine: The resolution, chiral analysis, and biological evaluation of four antipodal pairs. Chirality 1992, 4, 356-366.
6. Stanev, S.; Rakovska, R.; Berova, N.; Snatzke, G. Synthesis, absolute configuration and circular dichroism of some diarylmethane derivatives. Tetrahedron Asymmetry 1995, 6, 183-198.
7. Botta, M.; Summa, V.; Corelli, F.; Di Pietro, G.; Lombardi, P. Synthesis of aryl 2-benzofuranyl and 2-indolyl carbinols of high enantiomeric purity via palladium-catalyzed heteroannulation of chiral arylpropargylic alcohols. Tetrahedron Asymmetry 1996, 7, 1263-1266.
8. Torrens, A.; Castrillo, J.A.; Claparols, A.; Redondo, J. Enantioselective synthesis of (R)- and (S)-cizolirtine. Application of oxazaborolidine-catalyzed asymmetric borane reduction to azolyl phenyl ketones. Synlett 1999, 765-767.
9. Corey, E.J.; Helal, C.J. Reduction of carbonyl compounds with chiral oxazaborolidine catalysts: A new paradigm for enantioselective catalysis and a powerful new synthetic method. Angew. Chem. Int. Ed. 1998, 37, 1986-2012.
10. Corey, E.J.; Bakshi, R.K.; Shibata, S. Highly enantioselective borane reduction of ketones catalyzed by chiral oxazaborolidines. Mechanism and synthetic implications. J. Am. Chem. Soc. 1987, 109, 5551-5553.
11. Corey, E.J. New enantioselective routes to biologically interesting compounds. Pure Appl. Chem. 1990, 62, 1209-1216.
12. Ohkuma, T.; Koizumi, M.; Ikehira, H.; Yokozawa, T.; Noyori, R. Selective hydrogenation of benzophenones to benzhydrols. Asymmetric synthesis of unsymmetrical diarylmethanols. Org. Lett. 2000, 2, 659-662.
13. Noyori, R.; Ohkuma, T. Rapid, productive and stereoselective hydrogenation of ketones. Pure Appl. Chem. 1999, 71, 1493-1501.
14. Pu, L.; Yu, H.-B. Catalytic asymmetric organozinc additions to carbonyl compounds. Chem. Rev. 2001, 101, 757-824.
15. Bolm, C.; Hildebrand, J.P.; Muñiz, K.; Hermanns, N. Catalyzed asymmetric arylation reactions. Angew. Chem. Int. Ed. 2001, 40, 3284-3308.
16. Schmidt, F.; Stemmler, R.T.; Rudolph, J.; Bolm, C. Catalytic asymmetric approaches towards enantiomerically enriched diarylmethanols and diarylmethylamines. Chem. Soc. Rev. 2006, 35, 454-470.
17. Langer, F.; Schwink, L.; Devasagayaraj, A.; Chavant, P.-Y.; Knochel, P. Preparation of functionalyzed dialkylzincs via a boron-zinc exchange. Reactivity and catalytic asymmetric addition to aldehydes. J. Org. Chem. 1996, 61, 8229-8243.
18. Oppolzer, W.; Radinov, R.N.; Sayed, E.E. Catalytic asymmetric synthesis of macrocyclic (E)-allylic alcohols from ω-alkynals via intramolecular 1-alkenylzinc/aldehyde additions. J. Org. Chem. 2001, 66, 4766-4770.
19. Dahmen, S.; Brase, S. [2, 2] Paracyclophane-based N,O-ligands in alkenylzinc additions to Aldehydes. Org. Lett. 2001, 3, 4119-4122.
20. Bolm, C.; Rudolph, J. Catalyzed asymmetric aryl transfer reactions to aldehydes with boronic acids as aryl source. J. Am. Chem. Soc. 2002, 124, 14850-14851.
21. Rudolph, J.; Schmidt, F.; Bolm, C. Highly enantioselective synthesis of secondary alcohols using triphenylborane. Adv. Synth. Catal. 2004, 346, 867-872.
22. Braga, A.L.; Luedtke, D.S.; Vargas, F.; Paixao, M.W. Catalytic enantioselective arylation of aldehydes: Boronic acids as a suitable source of transferable aryl groups. Chem. Commun. 2005, 2512-2514.
23. Wu, X.-Y.; Liu, X.-Y.; Zhao, G. Catalyzed asymmetric aryl transfer reactions to aldehydes with boroxines as aryl source. Tetrahedron Asymmetry 2005, 16, 2299-2305.
24. Liu, X.-Y.; Wu, X.-Y.; Chai, Z.; Wu, Y.-Y.; Zhao, G.; Zhu, S.-Z. Highly effective and recyclable dendritic ligands for the enantioselective aryl transfer reactions to aldehydes. J. Org. Chem. 2005, 70, 7432-7435.
25. Bolm, C.; Schmidt, F.; Zani, L. Synthesis of new chiral hydroxy oxazolines and their use in the catalytic asymmetric phenyl transfer to aldehydes. Tetrahedron Asymmetry 2005, 16, 1367-1376.
26. Dahmen, S.; Lormann, M. Triarylborane ammonia complexes as ideal precursors for arylzinc reagents in asymmetric catalysis. Org. Lett. 2005, 7, 4597-4600.
27. Jia, X.-F.; Fang, L.; Lin, A.-J.; Pan, Y.; Zhu, C.-J. Highly efficient and facile aryl transfer to aldehydes using ArB(OH)2-GaMe3. Synlett 2009, 3, 495-499.
28. Ji, J.-X.; Wu, J.; Au-Yeung, T.-T.-L.; Yip, C.W.; Haynes, R.K.; Chan, A.S.C. Highly enantioselective phenyl transfer to aryl aldehydes catalyzed by easily accessible chiral tertiary aminonaphthol. J. Org. Chem. 2005, 70, 1093-1095.
29. Ito, K.; Tomita, Y.; Katsuki, T. Enantioselective phenyl transfer to aldehydes using 1,1'-bi-2-naphthol-3,3'-dicarboxamide as chiral auxiliary. Tetrahedron Lett. 2005, 46, 6083-6086.
30. Braga, A.L.; Milani, P.; Vargas, F.; Paixão, M.W.; Sehnem, J.A. Modular chiral thiazolidine catalysts in asymmetric aryl transfer reactions. Tetrahedron Asymmetry 2006, 17, 2793-2797.
31. Wu, P.-Y.; Wu, H.-L.; Uang, B.-J. Asymmetric synthesis of functionalized diarylmethanols catalyzed by a new γ-amino thiol. J. Org. Chem. 2006, 71, 833-835.
32. Lu, G.; Kwong, F.-Y.; Ruan, J.W.; Li, Y.-M.; Chan, A.S.C. Highly enantioselective addition of in situ prepared arylzinc to aldehydes catalyzed by a series of atropisomeric binaphthyl-derived amino alcohols. Chem. Eur. J. 2006, 12, 4115-4120.
33. Jin, M.J.; Sarkar, S.M.; Lee, D.H.; Qiu, H.L. Highly enantioselective aryl transfer to aldehydes: A remarkable effect of sulfur substitution in amino thioacetate ligands. Org. Lett. 2008, 10, 1235-1237.
34. Huang, X.-B.; Wu, L.-L.; Xu, J.-Q.; Zong, L.-L.; Hu, H.-W.; Cheng, Y.-X. Enantioselective arylation of aldehydes catalyzed by a soluble optically active polybinaphthols ligand. Tetrahedron Lett. 2008, 49, 6823-6826.
35. DeBerardinis, A.M.; Turlington, M.; Pu, L. Activation of functional arylzincs prepared from aryl iodides and highly enantioselective addition to aldehydes. *Org. Lett.* **2008**, *10*, 2709-2712.

36. Wang, M.-C.; Wang, X.-D.; Ding, X.; Liu, Z.-K. Catalytic asymmetric arylation of highly enantioselective addition to aldehydes. *Org. Lett.* **2008**, *10*, 2709-2712.

37. Ruan, J.-W.; Lu, G.; Xu, L.-J.; Li, Y.-M.; Chan, A.S.C. Catalytic asymmetric alkynylation and arylation of aldehydes by an H3-binaphthyl-based amino alcohol ligand. *Adv. Synth. Catal.* **2008**, *350*, 76-84.

38. Wang, M.-C.; Zhang, Q.-J.; Zhao, W.-X.; Wang, X.-D.; Ding, X.; Jing, T.-T.; Song, M.-P. N-(Ferrocenylmethyl)azetidin-2-yl(diphenyl)methanol for catalytic asymmetric addition of organozinc reagents to aldehydes. *J. Org. Chem.* **2008**, *73*, 168-176.

39. Braga, A.L.; Paixa, M.W.; Westermann, B.; Schneider, P.H.; Wessjohann, L.A. Acceleration of arylzinc formation and its enantioselective addition to aldehydes by microwave irradiation and aziridine-2-methanol catalysts. *J. Org. Chem.* **2008**, *73*, 2879-2882.

40. Salvi, L.; Kim, J.G.; Walsh, P.J. Practical catalytic asymmetric synthesis of diaryl-, aryl heteroaryl-, and diheteroaryl methylmethanols. *J. Am. Chem. Soc.* **2009**, *131*, 12483-12493.

41. Wouters, A.D.; Trossini, G.H.G.; Stefani, H.A.; Lüdtke, D.S. Enantioselective arylations catalyzed by carbohydrate-based chiral amino alcohols. *Eur. J. Org. Chem.* **2010**, 2351-2356.

42. Alexakis, A.; Mangeney, P. *Advanced Asymmetric Synthesis*; Stephenson, G.R., Ed.; Chapman & Hall: London, UK, 1996; Chapter 5, p. 93.

43. Bennani, Y.L.; Hannessian, S. Trans-1,2-diaminocyclohexane derivatives as chiral reagents, scaffolds, and ligands for catalysis: Applications in asymmetric synthesis and molecular recognition. *Chem. Rev.* **1997**, *97*, 3161-3195.

44. Lucet, D.; Le Gall, T.; Mioskowski, C. The chemistry of vicinal diamines. *Angew. Chem. Int. Ed.* **1998**, *37*, 2580-2627.

45. Hirama, M.; Oishi, T.; Ito, S. Asymmetric dihydroxylation of alkenes with osmium tetroxide: Chiral N, N'-dialkyl-2,2'-bipyrrrolidine complex. *Chem. Commun.* **1989**, *10*, 665-666.

46. Oishi, T.; Hirama, M. Highly enantioselective dihydroxylation of trans-disubstituted and monosubstituted olefins. *J. Org. Chem.* **1989**, *54*, 5834-5835.

47. Oishi, T.; Hirama, M.; Sita, L.R.; Masamune, S. Synthesis of chiral 2, 2'-bipyrrrolidine derivatives. *Synthesis* **1991**, 789-792.

48. Kotsuki, H.; Kuzume, H.; Gohda, T.; Fukuhara, M.; Ochi, M.; Oishi, T.; Hirama, M.; Shirot, M. New convenient, enantiospecific synthesis of (S, S)- and (R, R)-2,2'-bipyrrrolidine derivatives. *Tetrahedron Asymmetry* **1995**, *6*, 2227-2236.

49. Alexakis, A.; Tomassini, A.; Chouillet, C.; Roland, S.; Mangeney, P.; Bernardinelli, G. A new efficient synthesis of (R, R)-2,2'-bipyrrrolidine: An interesting chiral 1,2-diamine with C2 symmetry. *Angew. Chem. Int. Ed.* **2000**, *39*, 4093-4095.

50. Denmark, S.E.; Fu, J.-P.; Lawler, M.J. (R, R)-2,2'-bipyrrrolidine and (S, S)-2,2'-bipyrrrolidine: Useful ligands for asymmetric synthesis. *Org. Synth.* **2006**, *83*, 121-130.

51. Denmark, S.E.; Fu, J.-P. Catalytic, Enantioselective addition of substituted allylic trichlorosilanes using a rationally-designed 2,2'-bipyrrrolidine-based bisphosphoramidate. *J. Am. Chem. Soc.* **2001**, *123*, 9488-9489.
Molecules 2011, 16

52. Alexakis, A.; Andrey, O. Diamine-catalyzed asymmetric michael additions of aldehydes and ketones to nitrostyrene. *Org. Lett.* 2002, 4, 3611-3614.

53. Andrey, O.; Alexakis, A.; Bernardinelli, G. Asymmetric michael addition of α-Hydroxyketones to nitroolefins catalyzed by chiral diamine. *Org. Lett.* 2003, 5, 2559-2561.

54. Andrey, O.; Alexakis, A.; Tomassini, A.; Bernardinelli, G. The use of N-alkyl-2,2’-bipyrrrolidine derivatives as organocatalysts for the asymmetric michael addition of ketones and aldehydes to nitroolefins. *Adv. Synth. Catal.* 2004, 346, 1147-1168.

55. Mossé, S.; Alexakis, A. First organocatalyzed asymmetric michael addition of aldehydes to vinyl Sulfones. *Org. Lett.* 2005, 7, 4361-4364.

56. Alexakis, A.; Tomassini, A.; Andrey, O.; Bernardinelli, G. Diastereoselective alkylation of (arene)tricarbonylchromium and ferrocene complexes using a chiral, C2-symmetrical 1,2-diamine as auxiliary. *Eur. J. Org. Chem.* 2005, 1332-1339.

57. Denmark, S.E.; Fu, J.-P.; Lawler, M.J. Chiral phosphoramidate-catalyzed enantioselective addition of allylic trichlorosilanes to aldehydes. Preparative studies with bidentate phosphorus-based amides. *J. Org. Chem.* 2006, 71, 1523-1536.

58. Chen, M.S.; White M.C. A predictably selective aliphatic C-H oxidation reaction for complex molecule synthesis. *Science* 2007, 318, 783-787.

59. Suzuki, K.; Oldenburg, P.D.; Que, L., Jr. Iron-catalyzed asymmetric olefin cis-dihydroxylation with 97% enantiomeric excess. *Angew. Chem. Int. Ed.* 2008, 47, 1887-1889.

60. Sergeeva, E.; Kopilov, J.; Goldberg, I.; Kol, M. Salan ligands assembled around chiral bipyrrolidine: Predetermination of chirality around octahedral Ti and Zr centres. *Chem. Commun.* 2009, 21, 3053-3055.

61. Sergeeva, E.; Kopilov, J.; Goldberg, I.; Kol, M. 2,2’-Bipyrrrolidine versus 1,2-diaminocyclohexane as chiral cores for helically wrapping diamine-diolate ligands. *Inorg. Chem.* 2009, 48, 8075-8077.

62. Jia, Y.-X.; Zhu, S.-F.; Yang, Y.; Zhou Q.-L. Asymmetric friedel-crafts alkylations of indoles with nitroalkenes catalyzed by Zn(II)-bisoxazoline complexes. *J. Org. Chem.* 2006, 71, 75-80.

63. Arai, T.; Yokoyama, N. Tandem Catalytic Asymmetric friedel-crafts/henry reaction: Control of three contiguous acyclic stereocenters. *Angew. Chem. Int. Ed.* 2008, 47, 4989-4992.

Sample Availability: Samples of the compounds are available from the authors.

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