TÜBİTAK

Turkish Journal of Chemistry

http://journals.tubitak.gov.tr/chem/

Research Article

Turk J Chem
(2016) 40: 689 – 697

doi:10.3906/kim-1603-95

Newly synthesized furanoside-based NHC ligands for the arylation of aldehydes

Serpil DENİZALTI*, Fatma ÇETİN TELLİ*, Selin YILDIRAN, Azize Yeşim SALMAN, Bekir ÇETİNKAYA
Department of Chemistry, Ege University, İzmir, Turkey

Received: 22.03.2016 • **Accepted/Published Online:** 14.06.2016 • **Final Version:** 02.11.2016

Abstract: New furanoside-based NHC precursor salts (**2**) were synthesized using amino alcohols from the chloralose derivatives of glucose (**a**), galactose (**b**), and mannose (**c**). The novel compounds were fully characterized by ^{1}H NMR, ^{13}C NMR, and elemental analyses. The catalytic activities of these salts were tested in the arylation of aldehydes as catalysts that were generated in situ from $[RhCl(COD)]_2$. In addition, **2a** was converted to the rhodium complex **3a** in order to compare the results obtained in situ. The newly synthesized compounds were very efficient in terms of yield; nevertheless they did not exhibit a chiral induction.

Key words: N-heterocyclic carbene, carbohydrates, arylation of aldehydes, rhodium

1. Introduction

Diarylmethanols are important structural motifs for the synthesis of biologically and pharmaceutically active compounds.[1–4] In order to obtain these compounds, the addition of organometallic reagents to aldehydes has been listed among the general methods. Organolithium, magnesium, zinc, and copper compounds are the most widely used in arylation reactions. However, these reagents are toxic and sensitive to air and moisture.[5–10] In recent years, 1,2-addition of boronic acids to aldehydes catalyzed by rhodium complexes (especially N-heterocyclic carbene (NHC) complexes) has become a very useful approach to prepare such compounds due to their low toxicities, stabilities, and easy handling.[8,9,11–19] Moreover, NHCs have emerged as important ligands in organometallic catalysis. In contrast to phosphine complexes, their strong affinities with metals and better temperature, air, and moisture stabilities have increased their popularity as ligands. The steric and electronic properties of these ligands can also be modified by altering the substituents at the nitrogen atoms and heterocycle, which enable them to be used as ancillary ligands for the preparation of various complexes.[20–25] In the literature, several carbohydrate-containing NHCs have been synthesized that include a C_1, C_2, C_3, or C_6-pyranoside-scaffold.[26–35] However, just a few of them were used as catalysts in Suzuki–Miyaura,[31,32] olefin metathesis,[33] gold-catalyzed cyclopropanation reaction,[34] or hydrosilylation of ketones.[35] On the other hand, to the best of our knowledge, there is no report concerning the synthesis and usage of furanoside-based NHCs in the rhodium-catalyzed arylation of aldehydes.

Recently, a series of chiral Schiff base ligands were prepared using aminochloralose derivatives of glucose and galactose by our group.[36] These ligands were used as catalysts in the asymmetric Henry reaction in the presence of Cu(II) ions giving yields of up to 95% and enantiomeric excesses up to 91%.[36] In our previous study,

*Correspondence: serpil.denizalti@ege.edu.tr, fatma.cetin@ege.edu.tr

the synthesis of alkoxy-substituted NHC-Rh(I) complexes and their applications in the arylation reaction were also reported.[19] The chiral center in these complexes was an α-carbon atom attached to nitrogen. Therefore, the synthesis of a new family of C_6-furanoside-based NHCs from aminochloralose derivatives of glucose, galactose, and mannose was reported instead of Schiff base ligands, and their catalytic activities for Rh-catalyzed addition of phenylboronic acid to aldehydes were investigated. Furthermore, in this study, the effect of the substituent on the β-carbon atom attached to nitrogen was examined.

2. Results and discussion

2.1. Synthesis and characterization of NHC precursors (2a–c) and rhodium complex (3a)

The synthesis of aminochloralose derivatives (**a**, **b**) was reported by our group in a previous study.[36] In the present study, a new aminochloralose derivative (**c**) from D-mannose was synthesized by selective tosylation of the appropriate chloralose followed by azidation and reduction reactions (Figure 1).[36,37] In the ^{1}H and ^{13}C NMR spectra of the compound **c**, the H-1 and HC-CCl_3 proton resonances were detected at 6.06 and 5.72 ppm and 106.1 and 110.1 ppm, respectively, while the OCH_3 protons were examined at 3.90 ppm.

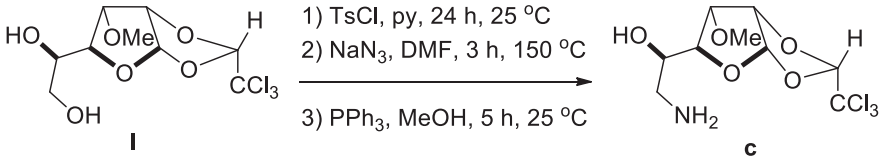

Figure 1. Synthesis of aminochloralose **c**.

The imidazolium salts (**2a**–**c**) were prepared by a two-step procedure, using aminochloralose derivatives as starting reagents (Figure 2). Firstly, 1-substituted imidazoles (**1a**–**c**) were obtained by the cyclocondensation of glyoxal, ammonium acetate, formaldehyde, and amino alcohol, using the previously published procedure.[38] The 1-substituted imidazoles (**1a**–**c**) were then readily converted into the desired imidazolium salts (**2a**–**c**), which were obtained as light brown solids.

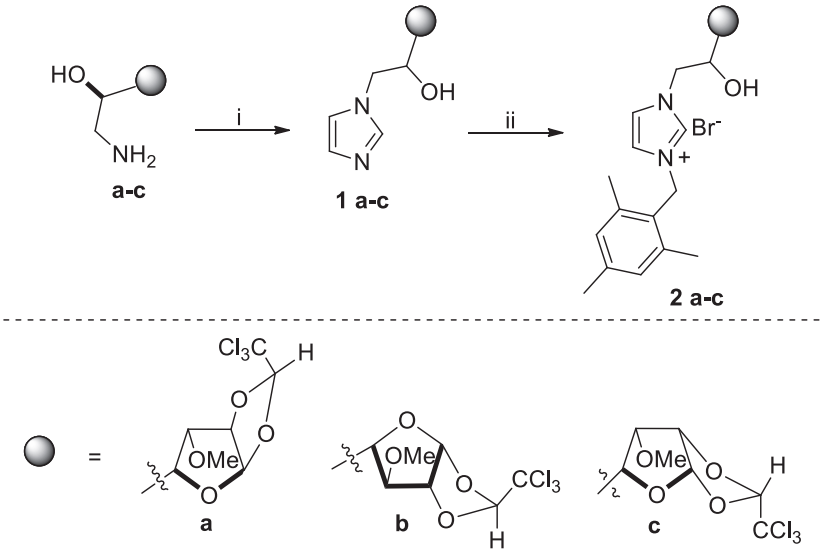

Figure 2. Reagents and conditions of reactions: (i) glyoxal, HCOOH, NH_4OAc, MeOH, reflux, 5 h; (ii) 2,4,6-$(CH_3)_3$-$C_6H_3CH_2Br$, CH_3CN, reflux.

The monosubstituted imidazoles (**1a**–**c**) and the imidazolium salts (**2a**–**c**) were characterized by spectroscopic methods. The ^{1}H and ^{13}C NMR spectra of the salts showed characteristic NCHN resonances between 9.33 and 9.65 ppm and at around 140.0 ppm, respectively. The signals of the imidazole ring resonances were observed at 6.77–7.50 ppm. NHC Rh(I) complex (**3a**) was synthesized by transmetallation of an NHC-silver(I) complex with $[RhCl(COD)]_2$ (Figure 3).[39–41] The synthesized complex **3a** was fully characterized by 2D-NMR (COSY, HSQC, HMQC) technique. In the ^{1}H NMR spectra of **3a**, the OH proton was not observed, which is consistent with previous reports.[19,42] It has also been demonstrated by Arnold's group, who prepared a variety of silver alkoxide NHCs, that silver(I) oxide is sufficiently basic to deprotonate both the imidazolium and the alcoholic functionalities.[19,42] Moreover, the characteristic downfield signals for the C2 hydrogens were not observed in the ^{1}H NMR spectra of the Rh(I) complexes. In the ^{13}C NMR spectra of **3a**, $C_{carbene}$ resonance was obtained at 180.1 ppm and the coupling constant $J(^{103}Rh - {}^{13}C)$ was calculated as 49.0 Hz.

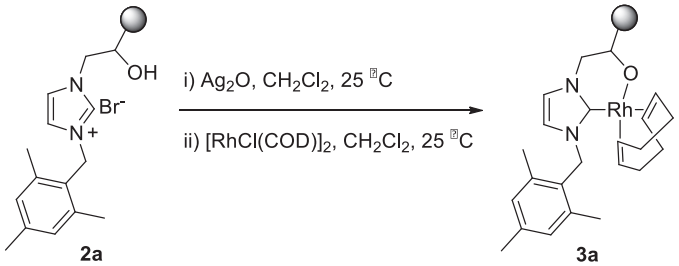

Figure 3. Synthesis of the rhodium complex **3a**.

2.2. Catalytic studies

The synthesized NHC ligands (**2a**–**c**) were tested in the 1,2-addition of phenylboronic acid to aldehydes. The effects of the solvent and the precatalyst loading on the arylation reaction between 2-chlorobenzaldehyde and phenylboronic acid were studied using **2a**/$[RhCl(COD)]_2$. DMF/H_2O, 1,4-dioxane/H_2O, THF/H_2O, *t*-amylalcohol/H_2O, DME/H_2O, and MeOH/DME (Table 1, entries 1–15) were used as solvents. MeOH and DME were found to serve as better solvents for the arylation reaction than the others in terms of yield. When MeOH, MeOH/DME, and DME/H_2O were used as solvents, the reaction catalyzed by **2a** was found to complete within 1 h (Table 1, Entries 1–3, 5). However, no enantioselectivity (or negligible *ee*) was observed under these conditions. In addition, increasing the catalyst loading and changing the solvent did not improve the enantioselectivity (Table 1, Entries 1–13). Comparing the data obtained here with our previous report[19] in terms of enantioselectivity revealed that the *ee* values could not be enhanced. However, the substituent on the β-carbon atom attached to nitrogen reduced the enantioselectivity.

The rhodium complex (**3a**) was also synthesized and tested in the arylation reaction. The results are comparable to those obtained in situ; therefore it was concluded that there is no need for the isolation and purification of the rhodium complexes (Table 1, Entry 7).

Under the optimized reaction conditions, the scope of the reaction was extended using a variety of aldehydes (Table 2). It was found that aldehydes bearing both electron-donating and electron-drawing substituents gave the diarylmethanols in good yields. However, moderate yields were obtained with 4-methoxybenzaldehyde (Table 2, Entry 6). In addition, the electron-poor aldehydes reacted with phenylboronic acid more easily than the electron-rich ones (Table 2). 2-Furaldehyde was also used as a substrate in the addition reaction, which afforded excellent yields (Table 2, Entry 8).

Table 1. The addition of phenylboronic acid to 2-chlorobenzaldehyde using **2a**–**c**.

Entry	Ligand (% mol)	Solvent	Yield (%)	TOF (h^{-1})	ee (%)
1	**2a**	MeOH	> 99	99	-
2	**2a**	MeOH/DME (5/1)	> 99	99	-
3	**2a**	MeOH/DME (3/1)	> 99	99	-
4	**2a**	DME/H_2O (3/1)	62	62	3
5	**2a**	DME/H_2O (5/1)	> 99	99	2
6	**2a**[a]	DME/H_2O (5/1)	41	41	2
7	**3a**	DME/H_2O (5/1)	97	97	2
8	**2a**	DMF/H_2O (3/1)	-	-	-
9	**2a**	THF/H_2O (3/1)	70	70	-
10	**2a**	*tert*-amyl alcohol/H_2O (3/1)	46	46	-
11	**2a**	Dioxane/H_2O (3/1)	73	73	3
12	**2a**[b]	Dioxane/H_2O (3/1)	98	98	4
13	**2a**[c]	Dioxane/H_2O (3/1)	97	97	-
14	**2b**	Dioxane/H_2O (3/1)	98	98	-
15	**2c**	Dioxane/H_2O (3/1)	91	91	-
16	**-**	Dioxane/H_2O (3/1)	5	5	-

Reaction conditions: ligand (1% mol), $[RhCl(COD)]_2$ (0.5% mol), aldehyde (0.5 mmol), KO^tBu (0.5 mmol), 80 °C, 1 h. [a] Determined by ^1H NMR analysis (average of two runs). [a] 30 min; [b] 3 mol% catalyst; [c] 5 mol% catalyst.

Table 2. The addition of phenylboronic acid to aldehydes.

Entry	Aldehyde	Ligand	t (h)	Yield (%)[a]
1	2-Cl-PhCHO	**2a**	1	> 99
		2b	1	> 99
		2c	1	> 99
2	4-Cl-PhCHO	**2a**	1	71
		2b	1	> 99
		2c	1	> 99
3	4-NO_2-PhCHO	**2a**	1	91
		2b	1	> 99
		2c	1	> 99
4	4-Me-PhCHO	**2a**	1	> 99
		2b	1	93
		2c	1	> 99
5	2-MeO-PhCHO	**2a**	4	> 99
		2b	4	> 99
		2c	4	> 99
6	4-MeO-PhCHO	**2a**	4	30
		2b	4	52
		2c	4	66
7	3,4,5-$(MeO)_3$-PhCHO	**2a**	4	98
		2b	4	92
		2c	4	> 99
8	2-Furaldehyde	**2a**	4	> 99
		2b	4	> 99
		2c	4	> 99

Reaction conditions: ligand (1% mol), $[RhCl(COD)]_2$ (0.5% mol), aldehyde (0.5 mmol), MeOH/DME (1.5/0.5 mL), KO^tBu (0.5 mmol), 80 °C. [a] Determined by ^1H NMR analysis (average of two runs).

In conclusion, in this study, NHC precursors bearing a furanoside scaffold (**2a**–**c**) were synthesized, characterized, and used in the arylation reaction of aldehydes for the first time. All of the ligand precursors showed excellent activity, resulting in complete conversions. Although attempts to achieve asymmetric induction failed, the yields of the diarylmethanols obtained are comparable or even higher than those reported in alternative procedures.[8,9,16,17,43–46]

3. Experimental

All manipulations were performed in air unless stated otherwise. All reagents were purchased from commercial sources and used as received. 2,4,6-Trimethylbenzyl bromide was as previously described.[47] Trichloroethylidene acetal of D-mannose (**I**),[48–51] aminochloralose derivatives (**a**–**c**),[36,37] and 1-substituted imidazoles (**1a**–**c**)[38] were prepared using a previously published procedure. The melting points were recorded with a Gallenkamp electrothermal melting point apparatus. The FTIR spectra were recorded on a PerkinElmer Spectrum 100 series. The ^{1}H NMR and ^{13}C NMR spectra were recorded with a Varian AS 400 Mercury instrument. Chemical shifts (δ) and coupling constants (J) were given in ppm and Hz, respectively. Optical rotations were recorded on a Rudolph Research Analytical Autopol I automatic polarimeter with a wavelength of 589 nm. The concentration 'c' has units of g/100 mL. Elemental analyses were performed on a PerkinElmer PE 2400 elemental analyzer.

3.1. Synthesis of 6-amino-6-deoxy-3-*O*-methyl-1,2-*O*-(*R*)-trichloroethylidene-β-D-mannofuranose (c)[36]

Yield: 76%. $[\alpha]_D^{23.5}$ = –31.25 (c 0.23 in CH_2Cl_2). IR cm^{-1} (KBr); 3299 (–NH_2 and –OH), 1591 (N–H), 1100 (–OMe). Anal. Calc. $C_9H_{14}Cl_3NO_5$: C, 33.51; H, 4.37; N, 4.34. Found: C, 33.45; H, 4.35; N, 4.29%. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 6.06 (d, J = 3.6 Hz, 1 H, H-1), 5.72 (s, 1 H, HC–CCl_3), 5.05 (dd, J = 3.6 Hz, 1 H,H-2), 4.02–4.07 (m, 2 H, H-3,H-4), 3.92 (m, 1 H, H-5), 3.90 (s, 3 H, OCH_3), 3.04, 2.81 (dd, J = 16.0, 4.0 Hz, 2 H, H-6), 1.70 (br s, 3 H, –NH_2, –OH). ^{13}C NMR: 110.1, 106.1 (HC–CCl_3, C-1), 99.4 (HC–CCl_3), 80.8, 80.2, 80.1 (C-2, C-3, C-4), 70.6 (C-5), 59.2 (OCH_3), 44.4 (C-6).

3.2. General procedure for the synthesis of 1-substituted imidazoles (1a–c)

Methanolic solution (6 mL) of glyoxal (40% w/v, 0.87 g, 6 mmol), ammonium acetate (0.46 g, 6 mmol), formaldehyde (36% w/v, 0.50 g, 6 mmol), and aminochloralose derivative (3 mmol) was refluxed for 5 h. The reaction mixture was concentrated by distillation. The residue was then treated with 2 M KOH solution (100 mL) and extracted with CH_2Cl_2 (4 × 100 mL). The combined organic phases were dried over Na_2SO_4 and concentrated in a vacuum.

1a: Yield: 90%. $[\alpha]_D^{23.2}$ = –8.70 (c 0.23 in CH_2Cl_2). Anal. Calc. $C_{12}H_{15}Cl_3N_2O_5$: C, 38.58; H, 4.05; N, 7.50. Found: C, 38.50; H, 6.79; N, 6.62%. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.40 (s, 1 H, NCHN), 6.90, 6.80 (s, 2 H, im–CH), 6.07 (d, J = 4.0 Hz, 1 H, H-1), 5.31 (s, 1 H, HC–CCl_3), 4.725 (d, J = 4.0 Hz, 1 H,H-2), 4.32 (dd, J = 4.0, 8.0 Hz, 1 H,H-4), 4.19–4.23 (m, 1 H, H-3), 4.07–4.14 (m, 2 H, H-6), 3.95–4.01 (m, 1 H, H-5), 3.47 (s, 3 H, OCH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.8 (NCHN), 128.1, 120.3 (im–CH), 107.1, 105.9 (HC–CCl_3, C-1), 96.7 (HC–CCl_3), 83.9, 82.8, 81.9 (C-2, C-3, C-4), 67.3 (C-5), 58.5 (OCH_3), 51.3 (C-6).

1b: Yield: 95%. $[\alpha]_D^{23.3}$ = –15.38 (c 0.26 in CH_2Cl_2). Anal. Calc. $C_{12}H_{15}Cl_3N_2O_5$: C, 38.58; H,

4.05; N, 7.50. Found: C, 38.49; H, 6.82; N, 6.63%. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.45 (s, 1 H, NC*H*N), 6.99, 6.96 (s, 2 H, im-C*H*), 6.21 (d, J = 4.0 Hz, 1 H, *H*-1), 5.71 (s, 1 H, *H*C–CCl_3), 5.29 (s, 1 H,*H*-4), 4.95 (d, J = 4.0 Hz, 1 H,*H*-2), 4.08–4.10 (m, 1 H, *H*-3), 3.93–3.96 (m, 3 H, *H*-5, *H*-6), 3.41 (s, 3 H, OCH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 138.2 (N*C*HN), 128.8, 119.8 (im–*C*H), 109.5, 107.0 (H*C*–CCl_3, *C*-1), 99.1 (HC–*C*Cl_3), 86.8, 86.7, 85.4 (*C*-2, *C*-3, *C*-4), 70.5 (*C*-5), 57.7 (O*C*H_3), 50.4 (*C*-6).

1c: Yield: 97%. $[\alpha]_D^{23.1}$ = –25.00 (c 0.24 in CH_2Cl_2). Anal. Calc. $C_{12}H_{15}Cl_3N_2O_5$: C, 38.58; H, 4.05; N, 7.50. Found: C, 38.51; H, 6.80; N, 6.62%. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.35 (s, 1 H, NC*H*N), 7.00, 6.98 (s, 2 H, im–C*H*), 6.10 (d, J = 4.0 Hz, 1 H, *H*-1), 5.66 (s, 1 H, *H*C–CCl_3), 5.06 (t, J = 4.0 Hz, 1 H,*H*-2), 4.22–4.27 (m, 1 H, *H*-3), 4.08–4.15 (m, 2 H, *H*-6), 3.93–3.99 (m, 2 H, *H*-5), 4.02 (t, J = 4.0 Hz, 1 H,*H*-4), 3.70–3.74 (m, 1 H, *H*-5), 3.55 (s, 3 H, OCH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ =138.3 (N*C*HN), 128.6, 120.4 (im–*C*H), 110.2, 106.3 (H*C*–CCl_3, *C*-1), 99.2 (HC–*C*Cl_3), 80.3, 80.2, 78.9 (*C*-2, *C*-3, *C*-4), 69.2 (*C*-5), 59.3 (O*C*H_3), 49.5 (*C*-6).

3.3. General procedure for the synthesis of imidazolium salts (2a–c)

1a–**c** (5.7 mmol) was dissolved in CH_3CN and 2,4,6-trimethylbenzyl bromide (5.7 mmol) was added. The mixture was refluxed overnight. The solvent was concentrated and Et_2O was added. The solid separated out was filtered and recrystallized from CH_2Cl_2/Et_2O.

2a: Yield: 71%. $[\alpha]_D^{23.3}$ = –9.09 (c 0.22 in CH_2Cl_2). Anal. Calc. $C_{22}H_{28}BrCl_3N_2O_5$: C, 45.04; H, 4.81; N, 4.77. Found: C, 44.99; H, 4.79; N, 4.75%. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 9.65 (s, 1 H, NC*H*N), 7.30, 6.77 (s, 2 H, im–C*H*), 6.93 (s, 2 H, $NCH_2C_6H_2(CH_3)_3$), 6.02 (d, J = 4.0 Hz, 1 H, *H*-1), 5.47 (s, 2 H, N*C*$H_2C_6H_2(CH_3)_3$), 5.25 (s, 1 H, *H*C–CCl_3), 4.87–4.90 (m, 1 H,*H*-5), 4.70 (d, J = 4.0 Hz, 1 H,*H*-2), 4.36–4.40 (m, 2 H, *H*-6), 4.19 (dd, 1 H,J= 4.0, 12.0 Hz, *H*-4), 4.02 (d, J = 4.0 Hz, 1 H, *H*-3), 3.48 (s, 3 H, OCH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 140.1 (N*C*HN), 138.1, 130.0, 129.9, 125.2, (Ar–*C*), 123.4, 119.9 (im–*C*H), 107.2, 105.9 (H*C*–CCl_3, *C*-1), 96.9 (HC–*C*Cl_3), 84.6, 82.4, 81.3 (*C*-2, *C*-3, *C*-4), 65.2 (N*C*$H_2C_6H_2(CH_3)_3$), 59.1 (*C*-5), 53.1 (*C*-6), 48.3 (O*C*H_3), 21.0, 19.9 ($NCH_2C_6H_2(CH_3)_3$).

2b: Yield: 82%. $[\alpha]_D^{23.1}$ = –18.18 (c 0.22 in CH_2Cl_2). Anal. Calc. $C_{22}H_{28}BrCl_3N_2O_5$: C, 45.04; H, 4.81; N, 4.77. Found: C, 45.01; H, 4.78; N, 4.74%. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 9.33 (s, 1 H, NC*H*N), 7.46, 6.89 (s, 2 H, im–C*H*), 6.94 (s, 2 H, $NCH_2C_6H_2(CH_3)_3$), 6.07 (d, J = 4.0 Hz, 1 H, *H*-1), 5.76 (s, 1 H, *H*C–CCl_3), 5.46 (s, 2 H, N*C*$H_2C_6H_2(CH_3)_3$), 4.56-4.60 (m, 1 H, *H*-5), 4.37-4.45 (m, 2 H, *H*-6), 4.24 (d, J = 4.0 Hz, 1 H,*H*-4), 4.16 (t, J = 4.0 Hz, 1 H, *H*-3), 3.43 (s, 3 H, OCH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 140.1 (N*C*HN), 138.3, 136.4, 130.0, 125.0 (Ar–*C*), 123.7, 120.3 (im–*C*H), 109.5, 107.3 (H*C*–CCl_3, *C*-1), 99.4 (HC–*C*Cl_3), 87.7, 87.1, 85.5 (*C*-2, *C*-3, *C*-4), 68.5 (N*C*$H_2C_6H_2(CH_3)_3$), 57.8 (*C*-5), 53.1 (*C*-6), 48.1 (O*C*H_3), 21.0, 19.9 ($NCH_2C_6H_2(CH_3)_3$).

2c: Yield: 81%. $[\alpha]_D^{23.1}$ = –19.05 (c 0.21 in CH_2Cl_2). Anal. Calc. $C_{22}H_{28}BrCl_3N_2O_5$: C, 45.04; H, 4.81; N, 4.77. Found: C, 45.02; H, 4.78; N, 4.76%. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 9.41 (s, 1 H, NC*H*N), 7.50, 6.95 (s, 2 H, im–C*H*), 6.92 (s, 2 H, $NCH_2C_6H_2(CH_3)_3$), 5.90 (d, J = 4.0 Hz, 1 H, *H*-1), 5.69 (s, 1 H, *H*C–CCl_3), 5.51 (s, 2 H, N*C*$H_2C_6H_2(CH_3)_3$), 5.09 (t, J = 4.0 Hz, 1 H, *H*-2), 4.54–4.61 (m, 2 H, *H*-6), 4.40–4.43 (m, 1 H, *H*-5), 4.03–4.05 (m, 2 H,*H*-3, H-4), 3.56 (s, 3 H, OCH_3). ^{13}C NMR (100 MHz, $CDCl_3$): δ = 140.0 (N*C*HN), 138.2, 136.9, 129.9, 125.2 (Ar–*C*), 123.2, 120.7 (im–*C*H), 110.0, 105.0 (H*C*–CCl_3, *C*-1),

98.4 (HC–CCl$_3$), 82.6, 81.4, 78.8 (C-2, C-3, C-4), 67.0 (NCH_2C$_6$H$_2$(CH$_3$)$_3$), 60.4 (C-5), 53.0 (C-6), 48.2 (OCH_3), 21.0, 19.9 (NCH$_2$C$_6$H$_2$(CH$_3$)$_3$).

3.4. Synthesis of rhodium complex 3a

Yield: 82%. Anal. Calc. C$_{30}$H$_{38}$Cl$_3$N$_2$O$_5$Rh: C, 50.33; H, 5.35; N, 3.91. Found: C, 49.27; H, 5.50; N, 3.89%. ^{1}H NMR (400 MHz, CDCl$_3$): δ = 6.92 (s, 2 H, NCH$_2$C$_6$$H_2$(CH$_3$)$_3$), 6.90, 6.77 (s, 2 H, im–CH), 6.15 (dd, J = 4.0, 19.6 Hz, 1 H, H-1), 5.73, 5.58 (d, J = 4.0, 14.4 Hz, 2 H, NCH_2C$_6$H$_2$(CH$_3$)$_3$), 5.29 (d, J = 8.0 Hz, 1 H, HC–CCl$_3$), 4.93–5.07 (m, 2 H, COD–CH), 4.89–3.99 (m, 1 H, H-5), 4.73–4.85 (m, 1 H, H-6), 4.74 (d, J = 4.0 Hz, 1 H, H-2), 4.40–4.47 (m, 1 H, H-6), 4.33 (m, 1 H, H-4), 4.11 (d, J = 4.0 Hz, 1 H, H-3), 3.42–3.58 (m, 2 H, COD–CH), 3.55 (s, 3 H, OCH_3), 2.26, 2.30 (s, 9 H, NCH$_2$C$_6$H$_2$(CH_3)$_3$), 2.34–2.52 (m, 4 H, COD–CH_2), 1.89–2.03 (m, 4 H, COD–CH_2). ^{13}C NMR (100 MHz, CDCl$_3$): δ = 180.1 (d, $J_{Rh,C}$ = 49.0 Hz, $C_{carbene}$), 138.5, 129.4, 128.6, 127.9, 123.2, 118.4 (Ar–C, im–C), 107.2, 106.2 (HC–CCl$_3$, C-1), 97.8, 98.4 (d, J = 6.6 Hz, COD–CH), 96.8 (HC–CCl$_3$), 84.6, 83.4, 82.9 (C-2, C-3, C-4), 68.4, 67.8 (d, J = 15.0 Hz, COD–CH), 66.5 (NCH_2C$_6$H$_2$(CH$_3$)$_3$), 59.3 (C-6), 54.8 (C-5), 49.3 (OCH_3), 33.3, 32.4, 28.8, 28.0 COD–CH_2), 21.0, 20.0 (NCH$_2$C$_6$H$_2$(CH$_3$)$_3$).

3.5. General procedure for the arylation of aldehydes

Phenylboronic acid (1 mmol), ligand (or complex **3a**) (0.01 mmol), [RhCl(COD)]$_2$ (0.005 mmol), and KO^{t}Bu (0.5 mmol) were successively added to a two-necked flask. The vessel was evacuated and flushed with argon three times. MeOH (1.5 mL) and DME (0.5 mL) were syringed, and then the aldehyde (1 mmol) was added to the mixture. The mixture was heated to 80 °C for 1 or 4 h. After cooling to ambient temperature, the reaction mixture was diluted with ethyl acetate (3 mL) and washed with water (2 mL). The organic phase was dried (Na$_2$SO$_4$) and evaporated in a vacuum. Yields were determined by ^{1}H NMR. The enantiomeric excesses were determined by HPLC using a chiral OJ-H column.

Acknowledgments

The authors acknowledge Ege University. We also thank Dr Levent Artok and Dr M Emin Günay for HPLC analyses.

References

1. Meguro, K.; Aizawa, M.; Sohda, T.; Kawamatsu, Y.; Nagaoka, A. *Chem. Pharm. Bull.* **1985**, *33*, 3787-3797.
2. Tada, F.; Tanaka, K.; Koshiro, K. *Tetrahedron: Asymmetry* **1991**, *2*, 873-874.
3. Bolm, C.; Hildebrand, J. P.; Muñiz, K.; Hermanns, N. *Angew. Chem. Int. Ed.* **2001**, *40*, 3284-3308.
4. Fagnou, K.; Lautens, M. *Chem. Rev.* **2003**, *103*, 169-196.
5. Noyori, R.; Kitamura, M. *Angew. Chem. Int. Ed.* **1991**, *30*, 49-69.
6. Soai, K.; Niwa, S. *Chem. Rev.* **1992**, *92*, 833-856.
7. Weber, B.; Seebach, D. *Tetrahedron* **1994**, *50*, 7473-7484.
8. Zhang, W.; Qin, Y.; Zhang, S.; Luo, M. *Arkivoc* **2005**, 39-48.
9. Chen, J.; Zhang, X.; Feng, Q.; Luo, M. *J. Organomet. Chem.* **2006**, *691*, 470-474.
10. Zheng, H.; Zhang, Q.; Chen, J.; Liu, M.; Cheng, S.; Ding, J.; Wu, H.; Su, W. *J. Org. Chem.* **2009**, *74*, 943-945.

11. Fürstner, A.; Krause, H. *Adv. Synth. Catal.* **2001**, 343-350.
12. Yiğit, M.; Özdemir, İ.; Çetinkaya, E.; Çetinkaya, B. *Heteroatom Chem.* **2005**, *6*, 461-465.
13. Özdemir, İ.; Gürbüz, N.; Gök, Y. *Trans. Metal. Chem.* **2005**, *30*, 367-371.
14. Gois, P. M. P.; Trindade, A. F.; Veiros, L. F.; André, V.; Duarte, M. T.; Afonso, C. A. M.; Caddick, S.; Cloke, F. G. N. *Angew. Chem. Int. Ed.* **2007**, *46*, 5750-5753.
15. Türkmen, H.; Denizaltı, S.; Özdemir, İ.; Çetinkaya, E.; Çetinkaya, B. *J. Organomet. Chem.* **2008**, *693*, 425-434.
16. He, Y.; Cai, C. *Chem. Commun.* **2011**, *47*, 12319-12321.
17. Busetto, L.; Cassani, M. C.; Femoni, C.; Mancinelli, M.; Mazzanti, A.; Mazzoni, R.; Solinas, G. *Organometallics* **2011**, *30*, 5258-5272.
18. Wang, D.; Ma, Y.; He, F.; Duan, W.; Zhao, L.; Song, C. *Synth. Commun.* **2013**, *43*, 810-825.
19. Denizaltı, S.; Türkmen, H.; Çetinkaya, B. *Tetrahedron Lett.* **2014**, *55*, 4129-4132.
20. Díez-González, S.; Marion, N.; Nolan, S. P. *Chem. Rev.* **2009**, *109*, 3612-3676.
21. Hahn, F. E.; Jahnke, M. C. *Angew. Chem. Int. Ed.* **2008**, *47*, 3122-3172.
22. Denizaltı, S.; Türkmen, H.; Çetinkaya, B. *Turk. J. Chem.* **2014**, *38*, 679-685.
23. Gürbüz, N.; Karaca, E. Ö.; Özdemir, İ.; Çetinkaya, B. *Turk. J. Chem.* **2015**, *39*, 1115-1157.
24. Herrmann, W. A. *Angew. Chem. Int. Ed.* **2002**, *41*, 1290-1309.
25. Günay, M. E.; Çoğaşlıoğlu, G. G.; Fırıncı, R. *Turk. J. Chem.* **2015**, *39*, 1310-1316.
26. Shi, J. C.; Lei, N.; Tong, Q.; Peng, Y.; Wei, J.; Jia, L. *Eur. J. Inorg. Chem.* **2007**, 2221-2224.
27. Nishioka, T.; Shibata, T.; Kinoshita, I. *Organometallics* **2007**, *26*, 1126-1128.
28. Frémont, P.; Stevens, E. D.; Eelman, M. D.; Fogg, D. E.; Nolan, S. P. *Organometallics* **2006**, *25*, 5824-5828.
29. Shibata, T.; Ito, S.; Doe, M.; Tanaka, R.; Hashimoto, H.; Kinoshita, I.; Yanod, S.; Nishioka, T. *Dalton Trans.* **2011**, *40*, 6778-6784.
30. Shibata, T.; Hashimoto, H.; Kinoshita, I.; Yanod, S.; Nishioka, T. *Dalton Trans.* **2011**, *40*, 4826-4829.
31. Yang, C. C.; Lin, P. S.; Liu, F. C.; Lin, I. J. B. *Organometallics* **2010**, *29*, 5959-5971.
32. Zhou, Z.; Qiu, J.; Xie, L.; Du, F.; Xu, G.; Xie, Y.; Ling, Q. *Catal Lett.* **2014**, *144*, 1911-1918.
33. Keitz, B. K.; Grubbs, R. H. *Organometallics* **2010**, *29*, 403-408.
34. Guitet, M.; Zhang, P.; Marcelo, F.; Tugny, C.; Jiménez-Barbero, J.; Buriez, O.; Amatore, C.; Mouriès-Mansuy, V.; Goddard, J. P.; Fensterbank, L.; et al. *Angew. Chem. Int. Ed.* **2013**, *52*, 7213-7218.
35. Henderson, A. S.; Bower, J. F.; Galan, M. C. *Org. Biomol. Chem.* **2014**, *12*, 9180-9183.
36. Alkan, S.; Telli, F. Ç.; Salman, Y.; Astley, S. T. *Carbohydrate Research* **2015**, *407*, 97-103.
37. Yenil, N.; Ay, E.; Ay, K.; Oskay, M.; Maddaluno, J. *Carbohydr. Res.* **2010**, *345*, 1617-1621.
38. Matsuoka, Y.; Ishida, Y.; Sasaki, D.; Saigo, K. *Tetrahedron* **2006**, *62*, 8199-8206.
39. Lin, J. C. Y.; Huang, R. T. W.; Lee, C. S.; Bhattacharyya, A.; Hwang, W. S.; Lin, I. J. B. *Chem. Rev.* **2009**, *109*, 3561-3598.
40. Garrison, J. C.; Youngs, W. J. *Chem. Rev.* **2005**, *105*, 3978-4008.
41. Wang, H. M. J.; Lin, I. J. B. *Organometallics* **1998**, *17*, 972-975.
42. Edworthy, I. S.; Rodden, M.; Mungur, S. A.; Davis, K. M.; Blake, A. J.; Wilson, C.; Schröder, M.; Arnold, P. L. *J. Organomet. Chem.* **2005**, *690*, 5710-5719.
43. Yan, C.; Zeng, X.; Zhang, W.; Luo, M. *J. Organomet. Chem.* **2006**, *691*, 3391-3396.
44. Arao, T.; Sato, K.; Kondo, K.; Aoyama, T. *Chem. Pharm. Bull.* **2006**, *54*, 1576-1581.

45. Kılınçarslan, R.; Yiğit, M.; Özdemir, İ.; Çetinkaya, E.; Çetinkaya, B. *J. Heterocyclic Chem.* **2007**, *44*, 69-73.
46. Türkmen, H.; Çetinkaya, B. *Appl. Organometal. Chem.* **2011**, *25*, 226-232.
47. Van der Made, A. W.; Van der Made, R. H. *J. Org. Chem.* **1993**, *58*, 1262-1263.
48. Heffter, A. *Ber. Dtsch. Chem. Ges.* **1889**, *22*, 1050-1051.
49. Anıl, H.; Yüceer, L.; Yüceer, T. *Carbohydr. Res.* **1983**, *123*, 153-156.
50. Salman, Y. G.; Kök, G.; Yüceer, L. *Carbohydr. Res.* **2004**, *339*, 1739-1745.
51. Yüceer, L. *Carbohydr. Res.* **1977**, *56*, 87-91.