Synthesis, characterization, and application of palladium complexes containing 8-quinolylphosphinite ligands

Earl Cook, Jason D. Masuda, and Aibing Xia

Abstract: Palladium complexes containing 8-quinolylphosphinite ligands have been synthesized and characterized. Their solid state structures were determined by single-crystal X-ray diffraction. They were found to be active catalysts for Suzuki coupling reactions of phenylboronic acid and various aryl halides.

Key words: palladium complexes, unsymmetrical ligands, quinoline, the Suzuki reaction.

Résumé : On a effectué la synthèse et caractérisé des complexes du palladium avec des ligands 8-quinolylphosphiniques. On a déterminé leur structures à l'état solide par diffraction des rayons X par un cristal unique. On a trouvé qu'ils sont actifs comme catalyseurs dans les réactions de couplage de Suzuki entre l'acide phénylboronique et divers halogénures d'aryle.

Mots-clés : complexes du palladium, ligands non symétriques, réaction de Suzuki.

[Traduit par la Rédaction]

Introduction

Unsymmetrical ligands with two or more different donors have attracted increasing attention due to their bonding versatility and catalytic applications. The combination of a soft donor and a hard donor induces different interactions between the metal centers and the unsymmetrical donors, which may lead to hemilabile properties.[1–3] The weak donors in the hemilabile ligands can dissociate from the metal center to facilitate substrate interaction, and rebind to the metal center to stabilize the reactive intermediates during catalytic cycles.

P,N-type ligands, containing strong donors such as phosphines and weak donors such as amines,[4–9] pyrazoles,[10,11] and pyridines[12–19] have been investigated in a variety of catalytic transformations. Recently Walther and co-workers[20] reported nickel complexes containing phosphinite ligands based on 8-hydroxyquinoline (Fig. 1, R = Ph, ^{i}Pr). The nickel diisopropylphosphinite complex was isolated, yet the diphenyl analogue was unstable and a tetrameric nickel complex was obtained instead. Very recently Crociani et al.[21] reported the synthesis of quinolylphosphinite palladium complexes containing di-*tert*-butyl groups (R = ^{t}Bu) and their catalytic applications. Here, we wish to report the synthesis, characterization, and catalytic applications of three new palladium complexes containing 8-quinolylphosphinites (R = Ph, ^{i}Pr, Cy).

Experimental

General

All experiments were performed under an argon atmosphere unless otherwise specified. All anhydrous solvents were purchased from Sigma-Aldrich Canada Ltd. and stored over 4 Å molecular sieves prior to use. 8-Hydroxyquinoline, chlorodiphenylphosphine, chlorodiisopropylphosphine, potassium hydride, and 4-*N*,*N*-dimethylaminopyridine (DMAP) were purchased from Sigma-Aldrich Canada Ltd. Bis(benzonitrile)dichloropalladium(II) and chlorodicyclohexylphosphine were purchased from Strem Chemicals, Inc. ^{1}H and ^{31}P NMR spectra were recorded on a Bruker Avance 500 spectrometer and referenced to SiMe$_4$ and 85% H_3PO_4, respectively. Infrared spectra were collected on a Nicolet Avatar 330 FT-IR spectrometer. Elemental analyses were carried out by Guelph Chemical Laboratories in Guelph, Ontario. Melting points were recorded on a Mel-Temp (Electrothermal) Apparatus and were uncorrected.

Complex 1

8-Hydroxyquinoline (0.145 g, 1.00 mmol) and DMAP (0.122 g, 1.00 mmol) were dissolved in THF (10 mL). Chlorodiphenylphosphine (0.221 g, 1.00 mmol) in THF (5 mL) was added dropwise. The mixture was stirred overnight and filtered. A solution of bis(benzonitrile)dichloropalladium(II) (0.384 g, 1.00 mmol) in CH_2Cl_2 (5 mL) was added to the filtrate. Yellow solids were formed after completion of the addition. The mixture was stirred overnight and filtered. The yellow solids were washed with hexane (2 × 5 mL). Yield 0.470 g (93%), mp 209 °C (dec). IR (KBr, cm^{-1}) ν: 2924 (m), 1655 (w), 1560 (w), 1508 (s), 1464 (m), 1437 (m), 1310 (m), 1253 (m), 1105 (s), 927 (w), 828 (m), 762 (w), 694 (w), 539 (w), 492 (w). ^{1}H NMR (500.13 MHz, CDCl$_3$, ppm) δ: 10.59 (dd, J = 1.5, 5.4 Hz, 1H, quinolyl), 8.44 (dd, J = 1.6, 8.3 Hz, 1H, quinolyl),

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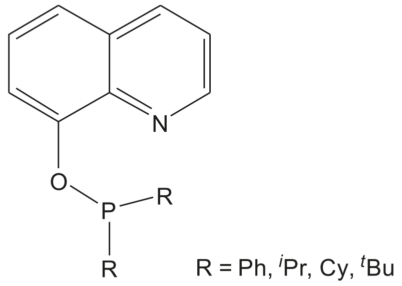
Fig. 1. 8-Quinolylphosphinites.



Scheme 1. Synthesis of palladium 8-quinolylphosphinite complexes.

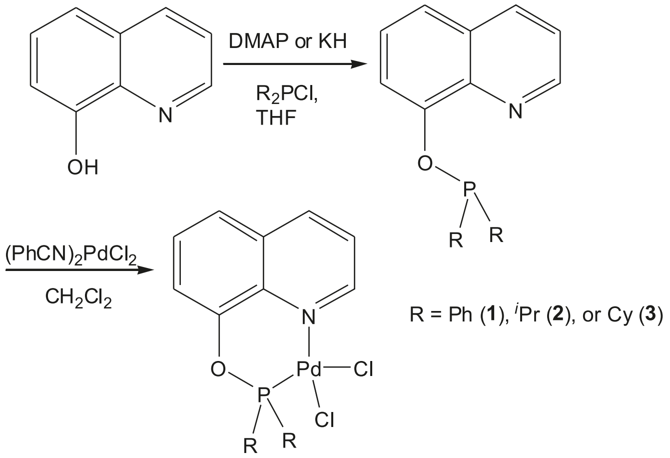
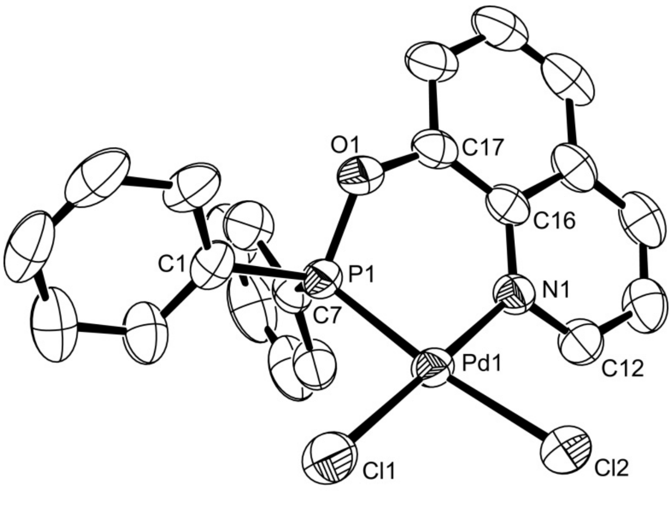


Fig. 2. Molecular structure of **1**.



7.97–7.93 (m, 4H, Ph), 7.74 (dd, J = 2.2, 7.6 Hz, 1H, quinolyl), 7.62–7.56 (m, 5H, overlapping quinolyl and Ph), 7.51–7.47 (m, 4H, overlapping quinolyl and Ph). ^{31}P NMR (202.47 MHz, $CDCl_3$, ppm) δ: 115.24. Anal. Calcd. for $C_{21}H_{16}Cl_2NOPPd$: C 49.78, H 3.18, N 2.76; found: C 50.16, H 3.38, N 2.77.

Table 1. Crystal data and structure refinement data for **1**.

Formula	$C_{21}H_{16}Cl_2NOPPd$
Formula weight	506.62
Crystal size (mm^3)	0.368×0.242×0.216
Space group	$P2(1)/n$
a (Å)	10.5513(4)
b (Å)	11.3256(4)
c (Å)	17.0524(6)
β (°)	99.2349(4)
V (Å^3)	2011.35(13)
Z	4
$D_{\mathrm{calcd.}}$ (g/cm^3)	1.673
μ (mm^{-1})	1.279
F(000)	1008
θ for data collection (°)	2.17–25.50
No. of total reflns.	13594
No. of unique reflns.	3731
R_1 ($I > 2\sigma(I)$)^a	0.0234
R_w (all data)^b	0.0636

^{a}$R = \Sigma(|F_o| - |F_c|) / \Sigma|F_o|$.

^{b}$R_w = [\Sigma w(F_o^2 - F_c^2)^2/\Sigma(F_o)^4]^{1/2}$ where $w = 1/[\sigma^2(F_o^2) + (0.0324 \times P)^2 + (0.6790 \times P)]$ where $P = (F_o^2 + 2F_c^2)/3$.

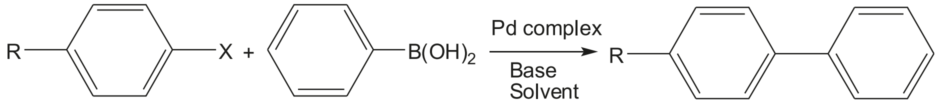
Table 2. Selected bond lengths (Å) and angles (°) for **1**.

Bond lengths (Å)	
Pd(1)—N(1)	2.0803(18)
Pd(1)—P(1)	2.1765(6)
Pd(1)—Cl(1)	2.2880(7)
Pd(1)—Cl(2)	2.3809(6)
Pd(1)—N(1)	2.0803(18)
Bond angles (°)	
N(1)–Pd(1)–P(1)	86.28(5)
N(1)–Pd(1)–Cl(1)	175.48(5)
P(1)–Pd(1)–Cl(1)	91.65(2)
N(1)–Pd(1)–Cl(2)	93.00(5)
P(1)–Pd(1)–Cl(2)	170.84(2)
Cl(1)–Pd(1)–Cl(2)	89.68(2)
N(1)–Pd(1)–P(1)	86.28(5)
N(1)–Pd(1)–Cl(1)	175.48(5)
P(1)–Pd(1)–Cl(1)	91.65(2)

Complex 2

8-Hydroxyquinoline (0.145 g, 1.00 mmol) was dissolved in THF (10 mL). Potassium hydride (KH, 0.080 g, 2.00 mmol) was added slowly. The mixture was stirred for 10 min and filtered to afford a fluorescent green solution. Chlorodiisopropylphosphine (0.155 g, 1.00 mmol) in THF (5 mL) was added dropwise. The mixture was stirred for 1 h. Bis(benzonitrile)dichloropalladium(II) (0.384 g, 1.00 mmol) in CH_2Cl_2 (5 mL) was added. The mixture was stirred overnight and filtered through celite. The volatiles were removed under vacuum to afford yellow solids. Yield 0.400 g (91%), mp 204–206 °C. IR (KBr, cm^{-1}) ν: 3448 (w), 2921 (m), 1590 (w), 1508 (s), 1465 (s), 1385 (m), 1310 (w), 1252 (m), 1104 (s), 932 (m), 842 (s), 825 (s), 758 (m), 667 (m). ^{1}H NMR (500.13 MHz, $CDCl_3$, ppm) δ: 10.49 (dd, J = 1.5, 5.4 Hz, 1H, quinolyl), 8.45 (dd, J = 1.4, 8.2 Hz, 1H, quinolyl), 7.75–7.72 (dd, J = 1.4, 8.2 Hz, 1H, quinolyl), 7.64 (t, J = 7.9 Hz, 1H, quinolyl), 7.58–7.55 (m, 2H, quinolyl), 2.87 (sept, J = 6.7 Hz, 2H, $CH(CH_3)_2$), 1.56 (d, J = 6.7 Hz, 6H, $CH(CH_3)'(CH_3)''$), 1.33 (d, J = 6.7 Hz, 6H, $CH(CH_3)'(CH_3)''$).

Table 3. Suzuki–Miyaura couplings using palladium complexes **1**–**3**.



Entry	Pd complex	Solvent	Base	R	X	Yield (%)[a]
1	**1**	1,4-Dioxane	K_3PO_4	CH_3O	Br	77
2	**1**	1,4-Dioxane	K_2CO_3	CH_3O	Br	57
3	**1**	1,4-Dioxane	Cs_2CO_3	CH_3O	Br	88
4	**1**	Toluene	Cs_2CO_3	CH_3O	Br	65
5	**1**	THF	Cs_2CO_3	CH_3O	Br	50
6	**1**	DMF	Cs_2CO_3	CH_3O	Br	96
7	**1**	DMF	Cs_2CO_3	NO_2	Cl	47
8	**3**	DMF	Cs_2CO_3	NO_2	Cl	44
9	**1**	DMF	Cs_2CO_3	NO_2	Cl	97[b]
10	**2**	DMF	Cs_2CO_3	NO_2	Cl	92[b]
11	**3**	DMF	Cs_2CO_3	NO_2	Cl	88[b]
12	**1**	DMF	Cs_2CO_3	CH_3	Cl	Trace
13	**2**	DMF	Cs_2CO_3	CH_3	Cl	Trace
14	**3**	DMF	Cs_2CO_3	CH_3	Cl	Trace
15	**1**	Toluene	K_2CO_3	$COCH_3$	Cl	5[c]
16	**2**	Toluene	K_2CO_3	$COCH_3$	Cl	61[c]
17	**3**	Toluene	K_2CO_3	$COCH_3$	Cl	60[c]

Note: Reaction conditions: 1.0 mmol aryl halide, 1.5 mmol phenyl boronic acid, 2.0 mmol base, 1 mol% palladium complex, 3 mL solvent, 100 °C, 18 h.

[a] GC yields based on aryl halides.

[b] 2 mol% palladium complex used.

[c] 110 °C, 2 h.

^{31}P NMR (202.47 MHz, $CDCl_3$, ppm) δ: 162.13. Anal. Calcd. for $C_{15}H_{20}Cl_2NOPPd$: C 41.07, H 4.60 N 3.19; found: C 41.16, H 4.88, N 3.13.

Complex 3

In a procedure similar to the preparation of **2**, complex **3** was obtained as yellow solids. Yield 0.490 g (94%), mp 235 °C (dec). IR (KBr, cm^{-1}) ν: 2931 (s), 2850 (m), 1593 (w), 1510 (m), 1465 (w), 1448 (w), 1388 (w), 1311 (w), 1258 (m), 1170 (w), 1101 (m), 1043 (w), 1002 (w), 933 (w), 886 (w), 856 (w), 831 (m), 762 (w), 726 (w), 696 (w), 571 (w), 560 (w), 531 (w). ^1H NMR (500.13 MHz, $CDCl_3$, ppm) δ: 10.48 (dd, J = 1.5, 5.4 Hz, 1H, quinolyl), 8.44 (dd, J = 1.4, 8.3 Hz, 1H, quinolyl), 7.72 (dd, J = 1.4, 8.2 Hz, 1H, quinolyl), 7.64 (t, J = 7.9 Hz, 1H, quinolyl), 7.58–7.55 (m, 2H, quinolyl), 2.69–2.61 (m, 2H, Cy), 1.91–1.72 (m, 12H, Cy), 1.41–1.25 (m, 6H, Cy). ^{31}P NMR (202.47 MHz, $CDCl_3$, ppm) δ: 155.82. Anal. Calcd. for $C_{21}H_{28}Cl_2NOPPd$: C 48.62, H 5.44, N 2.70; found: C 48.35, H 5.22, N 2.35.

X-ray crystallography

Crystals of **1**–**3** were grown by slow evaporation of solutions in CH_2Cl_2/hexane at room temperature. Single crystals were mounted in thin-walled capillaries. The data were collected using the Bruker APEX2 software package[22] on a Siemens diffractometer equipped with an APEXII CCD detector, a graphite monochromator, and MoKα radiation (λ = 0.71073 Å). A hemisphere of data was collected in 1664 frames with 10 s exposure times. Data processing and absorption corrections were applied using the APEX2 software package.[22] The structure was solved (direct methods) and all nonhydrogen atoms were refined anisotropically. Hydrogen atoms were placed in calculated positions using an appropriate riding model and coupled isotropic temperature factors. Thermal ellipsoid diagrams (50% probability level) were produced using Ortep-3 for Windows.[23]

Suzuki coupling reaction

General procedures for Suzuki reactions: a 20 mL reaction tube was charged with an aryl halide, phenylboronic acid, the palladium complex, and a base in 3 mL of solvent under argon and heated to 100 °C for 18 h. The mixture was then cooled to room temperature. The volatiles were removed under a reduced pressure. The organic product was extracted with ether and analyzed on an Agilent 6890 GC-FID instrument. The GC yield was calculated based on unreacted aryl halide and calibrated relative to standards containing aryl halide starting material and biphenyl product.

Results and discussion

Synthesis

The syntheses of 8-quinolylphosphinite ligands and their palladium complexes were outlined in Scheme 1. Deprotonation of 8-hydroxyquinoline with DMAP or potassium hydride, followed by reactions with chlorophosphines, gave the phosphinites. Due to their air-sensitive nature,[21] the phosphinites were used directly without further purification to react with bis(benzonitrile)dichloropalladium(II) to afford the corresponding palladium quinolylphosphinite complexes (**1**–**3**). All the complexes are air stable and can be stored and handled in air. They were also thermally robust, showing no sign of decomposition under 200 °C in air. They were characterized by ^1H and ^{31}P NMR spectroscopy and infrared (IR) spectroscopy. The solid state structures of the palladium complexes (**1–3**) were determined through X-ray diffraction studies. The elemental analysis results matched well with the expected values.

Characterization

The ^1H NMR spectra of the three palladium complexes contained chemical shifts for the quinolyl hydrogen around 10.5 ppm. This reflected a downfield shift of 1.5 ppm from the signal in the reported free ligands.[20,21] Other quinolyl hydrogens showed smaller shifts. The methyl groups in the isopropyl moieties in complex **2** became nonequivalent, reflecting the restriction of rotation of the isopropyl in the palladium complexes. The ^{31}P signals ranged from 115 to 162 ppm.

Suitable crystals of **1–3** for X-ray analysis were grown from slow evaporation of solutions of dichloromethane and hexane. The molecular structures of the complexes were almost identical. A representative structure of **1** is shown in Fig. 2. The structural data of **2** and **3** were included in the Supplementary data. Selected bond lengths and angles are listed in Table 1. Crystal data and structure refinement data are listed in Table 2. The structure of **1** showed a distorted square-planar geometry around the palladium ion, which bonded to the quinolylphosphinite P and N atoms as well as two Cl atoms. The bond angles of N–Pd–Cl(1) and P–Pd–Cl(2) are 175.5° and 170.8°, respectively. The bond lengths for Pd–P (2.177 Å), Pd–N (2.080 Å), and Pd–Cl (2.288 and 2.381 Å) are comparable to the reported values in related di-*tert*-butyl quinolylphosphinite palladium complexes.[21] The Pd–Cl(2) distance trans to the phosphorus is slightly longer than the Pd–Cl(1) distance trans to the nitrogen atom, suggesting a stronger trans effect of the phosphinite donor.

Catalytic studies

We evaluated the efficiency of the palladium phosphinite complexes in the Suzuki coupling reaction, one of the most important palladium-catalyzed cross-coupling carbon–carbon bond forming reactions in organic synthesis.[24–26] The results are listed in Table 3. For screening purposes, we used **1** as the palladium catalyst and chose 4-bromoanisole, a rather inert aryl bromide, as the organic substrate. We screened a few commonly used solvents and bases and found that Cs_2CO_3 and DMF led to the best yield (96%, Table 3, entry 6).

Under similar conditions, the palladium complexes gave moderate yields for the coupling of 4-chloronitrobenzene, an activated aryl chloride (Table 3, entries 7 and 8). When the palladium loading was increased to 2 mol%, excellent yields were obtained with all three complexes (Table 3, entries 9–11). However, the complexes were ineffective toward 4-chlorotoluene, a neutral aryl chloride (Table 3, entries 12–14). In comparison, the recently reported *tert*-butyl analogue gave complete conversion of both activated and nonactivated aryl chlorides in toluene.[21] When toluene was used as the solvent and K_2CO_3 as the base, **1–3** gave only low to modest yields for the coupling of 4′-chloroacetophenone (Table 3, entries 15–17). The higher efficiency of the *tert*-butyl analogue is likely due to its stronger donating ability and larger steric hindrance, which are beneficial factors for the Suzuki reactions of more challenging aryl chlorides.[25,26]

Conclusion

In summary, we have synthesized and characterized three palladium complexes containing 8-quinolylphosphinite ligands. The palladium complexes were easy to synthesize and stable in air. They were investigated in the Suzuki coupling reaction and showed excellent activity towards a deactivated aryl bromide but lower activity towards aryl chlorides.

Supplementary data

Supplementary data for this article are available on the journal Web site (canjchem.nrc.ca) or may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Ottawa, ON K1A 0R6, Canada. DUD 5317. For more information on obtaining material, refer to cisti-icist.nrc-cnrc.gc.ca/cms/unpub_e.shtml. CCDC 743458–743460 contain the X-ray data in CIF format for seven complexes for this manuscript. These data can be obtained, free of charge, via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax +44 1223 336033; or deposit@ccdc.cam.ac.uk).

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