Borylation of Arenes with Bis(hexylene glycolato)diboron

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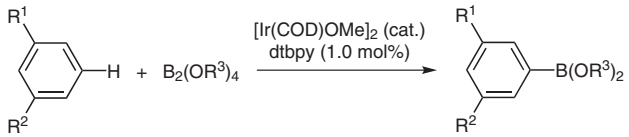
This paper is dedicated to Professor Scott Denmark on the occasion of his 60th birthday.

Abstract: A series of diolate-substituted diboron compounds were investigated as reagents for iridium-catalyzed C–H borylations of arenes. These studies showed that commercially available bis(hexylene glycolato)diboron reacts with arenes in the presence of the catalyst generated from $[Ir(COD)OMe]_2$ and di-*tert*-butylbipyridine. This reagent is prepared from a less expensive diol than the more commonly used bis(pinacolato)diboron reagent.

Key words: iridium, C–H borylation, bis(hexylene glycolato)diboron, arylboronate esters

Arylboronate esters are versatile synthetic intermediates that undergo Suzuki–Miyaura and Chan–Lam–Evans cross-coupling reactions to form C–C and C–X bonds.[1,2] A traditional method to form these aromatic organoboron reagents is the addition of a reactive organometallic species, such as an aryllithium or aryl Grignard reagent, to an electrophilic boron compound. More recently, metal-catalyzed reactions of aryl halides have been employed to form arylboronate esters.[3] The Ir-catalyzed C–H borylation of arenes (Scheme 1) has become a powerful method to access arylboronate esters directly from aryl C–H bonds instead of a prefunctionalized aryl halide.[4–6] Besides being a more facile approach to the synthesis of arylboronate esters than the borylation of aryl halides, the selectivity of the Ir-catalyzed C–H borylation of arenes is distinct. The regioselectivity of the C–H borylation of arenes is controlled by the steric properties of the substrate.[7] Therefore, it complements C–H functionalization methods that rely on directing groups[8–10] and Friedel–Crafts reactions of electron-rich substrates that are controlled by the electronic properties of the arene.



Scheme 1 Iridium-catalyzed borylation of arenes

Although the scope of the arenes that undergo Ir-catalyzed C–H borylation is broad, and many functional groups are tolerated, the scope of the diboron reagents that undergo C–H borylation is limited. Only a few boron reagents undergo Ir-catalyzed C–H functionalization reactions. Most commonly, the C–H borylation of arenes is conducted with bis(pinacolato)diboron (B_2pin_2) or pinacolborane (HBpin) as the boron source. In addition to the wide range of reports on the reactions of this reagent, Suginome and co-workers reported the C–H borylation with 1,8-naphthalenediaminatoborane (HBdan) as the boron reagent,[11] and our group reported the C–H borylation of arenes with bis(catecholato)diboron (B_2cat_2).[12] Both reagents were less reactive for the C–H borylation of arenes than B_2pin_2 and required neat substrate to obtain significant yields.

We have proposed that the origin of this difference in reactivity stems from electronic effects. The addition of B_2pin_2 to the iridium center forms a more electron-rich complex than that from addition of B_2cat_2, and the C–H bond cleavage of arenes by a complex containing a more electron-rich metal center occurs faster than that by a complex containing a more electron-poor metal center.[12,13]

Although the C–H borylation occurs with the highest turnover numbers with B_2pin_2 as the boron reagent, the pinacolate ester products generated in these reactions are typically less reactive towards subsequent functionalization than those generated from boron reagents. For instance, copper-mediated Chan–Lam–Evans coupling with arylamines and phenols required initial oxidative hydrolysis of the boronate ester to the corresponding boronic acid.[2,14] The oxidative hydrolysis of the pinacolate esters is typically conducted with $NaIO_4$, which can react with functional groups or heteroarenes that are sensitive to oxidative conditions, thereby limiting the scope of the reactions of pinacol esters.[15]

One reason for this lack of reactivity is likely to be a difference in the rate of transmetalation of the pinacol boronates and boronic acids or the catecholate esters. Transmetalation of the pinacol boronates to palladium has been shown to be slower than transmetalation of the boronic acids or other less hindered esters.[16]

One final issue concerning the chemistry of pinacol boronate esters is the cost of pinacol. The largest contributor to the materials cost of the B_2pin_2 reagent is pinacol. If a reagent could be developed that contained a less expensive diol, then the cost of the overall C–H borylation process could be reduced and could be made even more practical for implementation on a large-scale. Hence, the investigation of other boron reagents for the C–H borylation of arenes has been an active area of research. Here, we report

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the C–H borylation of arenes with a series of diboron reagents and the identification of the reagent containing hexylene glycol as one of the more reactive alternatives.

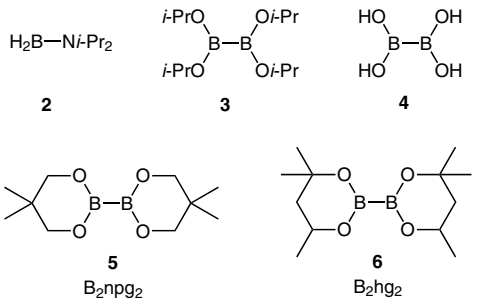


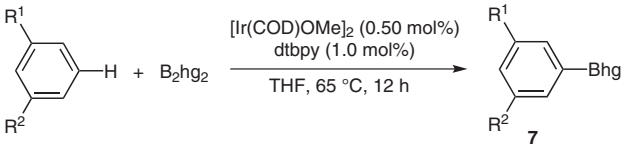
Figure 1 Boron reagents examined in the C–H borylation of arenes

Our studies on boron reagents for the C–H borylation of arenes began with the reaction of 1,3-bis(trifluoromethyl)benzene (**1**), which is one of the most reactive arenes for C–H borylation reactions. These reactions were conducted with a series of boron reagents in the presence of 2.5 mol% $[Ir(COD)OMe]_2$ (COD = cyclooctadiene) and 5.0 mol% 4,4′-di-*tert*-butylbipyridine (dtbpy) (Figure 1). The C–H borylation does not occur with acyclic aminoboron **2** or dialkoxyboron **3** reagents. Reactions conducted in the presence of the bis-boronic acid **4** did not lead to detectable amounts of borylation product. Analysis of the stoichiometric reaction of **4** with $(dtbpy)Ir(Bpin)_3(COE)$, a precursor to the intermediate in the C–H borylation of arenes,[13] by ^{11}B NMR spectroscopy showed immediate decomposition of the Ir–trisboryl complex in the presence of bis-boronic acid, presumably from protonation of the boryl ligands.

The borylation does occur with the commercially available diboron reagents bis(neopentyl glycolato) diboron (**5**, B_2npg_2) and bis(hexylene glycolato)diboron (**6**, B_2hg_2). Both boron reagents led to a high yield (>90% yield) of the arylboron product with neat activated arenes. However, reactions of B_2npg_2 with less activated arenes, such as 3-chlorotoluene, required neat arene, while the reactions of B_2hg_2 with 3-chlorotoluene could be conducted in THF solvent with only 1% catalyst loadings.

Having identified B_2hg_2 as an alternative boron reagent for the C–H borylation of arenes, the scope of the reactions of this reagent was investigated. The C–H borylation of 1,3-disubstituted arenes was shown to occur in the presence of B_2hg_2, $[Ir(COD)OMe]_2$, and dtbpy in THF at 65 °C over 12 hours in good yield (Table 1). The borylation of electron-deficient arenes occurred in higher yield and lower catalyst loadings than those of electron-rich arenes (entries 1 and 2). Arenes containing halogen substituents underwent the borylation in high yields to generate the corresponding *meta*-substituted boronate esters (entries 4–7). Consistent with prior observations during studies on Ir-catalyzed C–H borylation reactions conducted with B_2pin_2, the C–H functionalization was shown to occur at the C–H bond located *ortho* to small substituents, such as fluorine (entry 5). Finally, a range of functional groups are tolerated, including ketones, protected alcohols, amides, and esters (entries 6–9).

Table 1 Scope of the Borylation of Arenes with Bis(hexylene glycol)diboron[a]



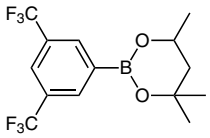
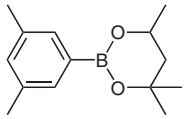
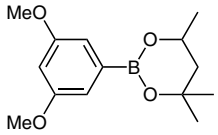
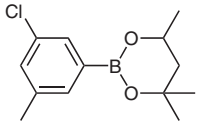
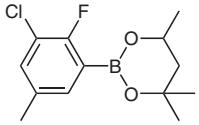
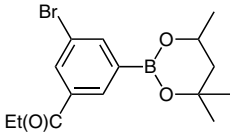
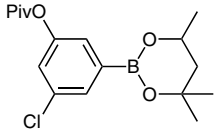
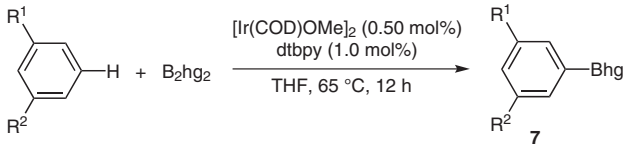
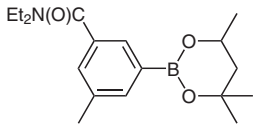
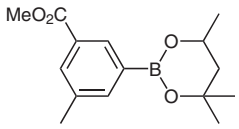
Entry	Product	Yield (%)
1	 **7a**	98[b]
2	 **7b**	50[c]
3	 **7c**	62
4	 **7d**	86
5	 **7e**	86
6	 **7f**	67
7	 **7g**	96

Table 1 Scope of the Borylation of Arenes with Bis(hexylene glycol)diboron[a] (continued)



7

Entry	Product	Yield (%)
8	 **7h**	64[d]
9	 **7i**	67

[a] Reactions conducted with 1.0 mmol arene and 1.0 mmol diboron reagent. Products isolated by silica gel chromatography.
[b] Reaction conducted with 0.25 mol% $[Ir(COD)OMe]_2$ and 0.50 mol% dtbpy.
[c] Reaction conducted with 5.0 mol% $[Ir(COD)OMe]_2$ and 10 mol% dtbpy.
[d] Reaction conducted with 2.5 mol% $[Ir(COD)OMe]_2$ and 5.0 mol% dtbpy.

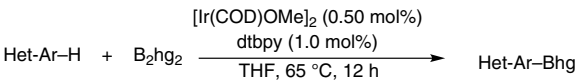
Heteroarenes also undergo borylation with B_2hg_2 in good yield (Table 2). Five-membered heteroarenes, including pyrroles and furans containing a substituent at the 2-position, react at the 5-position to generate 5-borylheteroarenes in good yields (entries 1 and 2). The borylation of furan occurred to give two isomers of the product (91:9 ratio). Benzo-fused heteroarenes also reacted at the 2-position. Indole and benzofuran underwent the borylation reaction in good yields (entries 3 and 4), while benzothiophene required higher catalyst loadings and gave a lower yield of the product (entry 5) than reactions of the other five-membered heteroarenes. Finally, the borylation occurred with a 2,6-disubstituted pyridine to generate the 4-borylpyridine product (entry 6).

The arylboronate esters generated from these C–H borylation reactions have been generated previously through nucleophilic attack on an electrophilic boron reagents[17] and through Miyaura borylations reactions of aryl halides.[18,19] These hexylene glycolate boronate esters undergo Suzuki–Miyaura coupling reactions.

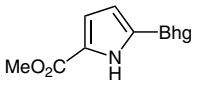
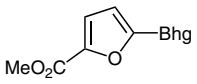
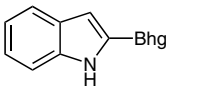
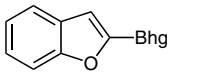
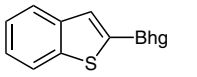
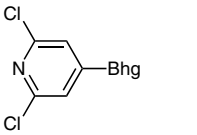
One advantage of this boron reagent is the low cost of hexylene glycol.[20] Although the corresponding diboron reagent is currently more expensive than B_2pin_2, B_2hg_2 has the potential to be less expensive than B_2pin_2 in the future, particularly on a large scale.

In conclusion, a series of boron reagents were investigated for the C–H borylation of arenes. Of these reagents, a diboron compound containing hexylene glycol substituents

Table 2 Scope of the Borylation of Heteroarenes with Bis(hexylene glycolato)diboron[a]



8

Entry	Product	Yield (%)
1	 **8a**	94
2	 **8b**	92[b]
3	 **8c**	93
4	 **8d**	94
5	 **8e**	52[c]
6	 **8f**	74[d]

[a] Reactions conducted with 1.0 mmol arene and 1.0 mmol diboron reagent. Products isolated by silica gel chromatography.
[b] Two isomers were formed in a 91:9 ratio.
[c] Reaction conducted with 2.5 mol% $[Ir(COD)OMe]_2$ and 5.0 mol% dtbpy.
[d] Reaction conducted with 4.0 mol% $[Ir(COD)OMe]_2$ and 8.0 mol% dtbpy.

on boron was the most reactive for the borylation of arenes. A higher catalyst loading was required to achieve good yields for the reactions of B_2hg_2 as the boron reagent than for the reactions conducted with B_2pin_2; however, studies on the reactivity of these boronate esters are ongoing and new catalysts should be tested for reactions of this reagent.

All borylation reactions were conducted under an argon atmosphere in a Braun drybox. $[Ir(COD)OMe]_2$ was obtained from Johnson Mathey and stored at –35 °C in the glovebox. 4,4′-Di-*tert*-butyl-2,2′-bipyridine (dtbpy), and the arene substrates were purchased from Sigma-Aldrich and used as received. Borylation reactions were performed using THF that was degassed by purging with argon for 45 min and then dried with a solvent purification system using a 1-m column containing activated alumina. Bis(hexylene glycolato)diboron (B_2hg_2) was purchased from Combi-Blocks and

used as received. Flash column chromatography was performed on Silicycle Siala-P silica gel or on a Teledyne Isco CombiFlash Rf automated chromatography system with 4 g RediSep Rf Gold normal-phase silica columns. Products were visualized on TLC plates by a 254 nm UV lamp or by staining with CAM or $KMnO_4$. GC-MS data were obtained on an Agilent 6890-N GC system containing an Alltech EC-1 capillary column and an Agilent 5973 mass selective detector. NMR spectra were acquired on 400 MHz Bruker, or 600 Bruker spectrometers, at University of California, Berkeley NMR facility, relative to a residual solvent peak [$CDCl_3$ δ = 7.26 (^{1}H) and 77.23 (^{13}C)]. Mass spectroscopy analyses were performed at the University of California, Berkeley Mass Spectroscopy Center.

Arene C–H Borylation with Bis(hexylene glycolato)diboron; General Procedure

In an argon-filled glove box, arene (1.0 mmol), bis(hexylene glycolato)diboron (254 mg, 1.0 mmol), $[Ir(COD)(OMe)]_2$ (3.3 mg, 5.0 μmol, 0.50 mol%), dtbpy (2.7 mg, 10.0 μmol, 1.0 mol%), and THF (1 mL) were added to a 4-mL vial with a stir bar. The mixture was heated in a sealed vessel at 65 °C for 12 h. The red soln was allowed to cool to r.t., and the volatile materials were evaporated under reduced pressure for 2 h. The crude mixture was purified by column chromatography to give the borylarene.

2-[3,5-Bis(trifluoromethyl)phenyl]-4,4,6-trimethyl-1,3,2-dioxaborinane (7a)

White solid; yield: 324 mg (98%).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 8.22 (s, 2 H), 7.88 (s, 1 H), 4.38 (dqd, *J* = 12.3, 6.2, 2.9 Hz, 1 H), 1.92 (dd, *J* = 14.0, 2.9 Hz, 1 H), 1.62 (m, 1 H), 1.41 (s, 3 H), 1.39 (s, 3 H), 1.38 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 133.70, 130.50, 130.28, 124.61, 123.75, 122.80, 71.86, 65.56, 45.95, 31.06, 28.07, 22.99.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{14}H_{15}BF_6O_2$: 340.1069; found: 340.1069.

2-(3,5-Dimethylphenyl)-4,4,6-trimethyl-1,3,2-dioxaborinane (7b)

White solid; yield: 116 mg (50%).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.44 (s, 2 H), 7.05 (s, 1 H), 4.35 (dqd, *J* = 12.3, 6.2, 3.0 Hz, 1 H), 2.33 (s, 6 H), 1.87 (dd, *J* = 13.9, 2.9 Hz, 1 H), 1.59 (m, 1 H), 1.39 (s, 3 H), 1.37 (s, 3 H), 1.36 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 136.69, 132.01, 131.38, 70.87, 64.92, 46.06, 31.30, 28.13, 23.25, 21.25.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{14}H_{21}BO_2$: 232.1635; found: 232.1636.

2-(3,5-Dimethoxyphenyl)-4,4,6-trimethyl-1,3,2-dioxaborinane (7c)

White solid; yield: 164 mg (62%).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 6.97 (d, *J* = 2.4 Hz, 2 H), 6.52 (t, *J* = 2.4 Hz, 1 H), 4.34 (dqd, *J* = 12.3, 6.2, 2.9 Hz, 1 H), 3.82 (s, 6 H), 1.86 (dd, *J* = 13.9, 2.9 Hz, 1 H), 1.58 (m, 1 H), 1.37 (s, 3 H), 1.36 (s, 3 H), 1.34 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 160.23, 110.90, 103.14, 71.06, 65.05, 55.28, 45.98, 31.23, 28.12, 23.17.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{14}H_{21}BO_4$: 264.1533; found: 264.1540.

2-(3-Chloro-5-methylphenyl)-4,4,6-trimethyl-1,3,2-dioxaborinane (7d)

White solid; yield: 216 mg (86%).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.57 (s, 1 H), 7.48 (s, 1 H), 7.18 (d, *J* = 12.2 Hz, 1 H), 4.34 (dqd, *J* = 12.3, 6.2, 2.9 Hz, 1 H), 2.32 (d, *J* = 18.7 Hz, 3 H), 1.87 (dd, *J* = 13.9, 2.9 Hz, 1 H), 1.58 (t, *J* = 12.8 Hz, 1 H), 1.38 (s, 3 H), 1.36 (s, 3 H), 1.35 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 138.80, 133.50, 132.44, 130.89, 130.63, 71.25, 65.15, 45.96, 31.21, 28.11, 23.14, 21.05.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{13}H_{18}BClO_2$: 252.1088; found: 252.1092.

2-(3-Chloro-2-fluoro-5-methylphenyl)-4,4,6-trimethyl-1,3,2-dioxaborinane (7e)

White solid; yield: 232 mg (86%).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.34 (br s, 1 H), 7.21 (br s, 1 H), 4.37 (dqd, *J* = 12.3, 6.2, 3.0 Hz, 1 H), 2.28 (s, 3 H), 1.88 (dd, *J* = 14.0, 2.9 Hz, 1 H), 1.62 (dd, *J* = 13.7, 12.0 Hz, 1 H), 1.38 (s, 6 H), 1.35 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 159.88 (d, *J* = 250.7 Hz), 134.38 (d, *J* = 7.6 Hz), 133.63 (d, *J* = 4.5Hz), 132.72, 120.32, (d, *J* = 21.1 Hz), 71.66, 65.47, 45.89, 31.13, 28.09, 23.06, 20.35.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{13}H_{17}BClFO_2$: 270.0997; found: 270.0999.

1-[3-Bromo-5-(4,4,6-trimethyl-1,3,2-dioxaborinan-2-yl)phenyl]propan-1-one (7f)

White solid: yield: 230 mg (67%).

IR: 1691 cm^{-1} (C=O).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 8.22 (s, 1 H), 8.10 (s, 1 H), 8.07 (s, 1 H), 4.35 (dqd, *J* = 12.2, 6.1, 2.9 Hz, 1 H), 3.02 (q, *J* = 7.2 Hz, 2 H), 1.89 (dd, *J* = 14.0, 2.8 Hz, 1 H), 1.61 (m, 1 H), 1.39 (s, 3 H), 1.37 (s, 3 H), 1.36 (d, *J* = 6.2 Hz, 3 H), 1.22 (t, *J* = 7.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 200.04, 140.83, 137.95, 132.50, 131.65, 122.72, 71.62, 65.39, 45.95, 31.93, 31.14, 28.11, 23.06, 8.09.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{15}H_{20}BBrO_3$: 338.0689; found: 338.0691.

3-Chloro-5-(4,4,6-trimethyl-1,3,2-dioxaborinan-2-yl)phenyl Pivalate (7g)

White solid; yield: 325 mg (96%).

IR: 1756 cm^{-1} (C=O).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.62 (d, *J* = 1.0 Hz, 1 H), 7.32 (t, *J* = 7.2 Hz, 1 H), 7.10 (t, *J* = 1.9 Hz, 1 H), 4.33 (dqd, *J* = 12.1, 6.1, 2.9 Hz, 1 H), 1.87 (dd, *J* = 14.0, 2.8 Hz, 1 H), 1.62–1.52 (m, 1 H), 1.37 (s, 3 H), 1.35 (d, *J* = 2.6 Hz, 12 H), 1.34 (d, *J* = 6.3 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 176.79, 151.05, 133.90, 130.96, 124.62, 123.80, 71.47, 65.28, 45.95, 39.04, 31.55, 31.13, 28.09, 27.10, 23.06, 22.62.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{17}H_{24}BClO_4$: 338.1456; found: 338.1459.

***N*,*N*-Diethyl-3-methyl-5-(4,4,6-trimethyl-1,3,2-dioxaborinan-2-yl)benzamide (7h)**

Colorless oil; yield: 203 mg (64%).

IR: 1635 cm^{-1} (C=O).

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.62 (s, 1 H), 7.60 (s, 1 H), 7.21 (s, 1 H), 4.33 (ddd, *J* = 11.5, 6.1, 2.9 Hz, 1 H), 3.53 (s, 2 H), 3.24 (s, 2 H), 2.36 (d, *J* = 5.0 Hz, 3 H), 1.90–1.81 (m, 1 H), 1.62–1.52 (m, 1 H), 1.36 (s, 3 H), 1.35 (d, *J* = 5.0 Hz, 3 H), 1.33 (d, *J* = 6.2 Hz, 3 H), 1.25 (d, *J* = 6.2 Hz, 3 H), 1.10 (s, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 171.96, 136.91, 136.29, 135.02, 128.84, 128.68, 71.06, 65.02, 45.99, 43.25, 39.07, 31.23, 28.12, 23.16, 21.26, 14.12, 12.90.

HRMS (EI): *m*/*z* $[M + H]^+$ calcd for $C_{18}H_{29}BNO_3$: 318.2235; found: 318.2237.

Methyl 3-Methyl-5-(4,4,6-trimethyl-1,3,2-dioxaborinan-2-yl)benzoate (7i)
White solid; yield: 184 mg (67%).

IR: 1723 cm^{-1} (C=O).

^1H NMR (600 MHz, $CDCl_3$): δ = 8.25 (s, 1 H), 7.88 (s, 1 H), 7.79 (s, 1 H), 4.35 (dqd, *J* = 12.3, 6.2, 3.0 Hz, 1 H), 3.90 (s, 3 H), 2.39 (s, 3 H), 1.88 (dd, *J* = 13.9, 2.9 Hz, 1 H), 1.60 (t, *J* = 12.6, 1 H), 1.39 (s, 3 H), 1.37 (s, 3 H), 1.36 (d, *J* = 6.4 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 167.73, 139.02, 137.04, 132.09, 131.96, 129.22, 71.21, 65.13, 51.90, 46.01, 31.23, 28.14, 23.17, 21.15.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{15}H_{21}BO_4$: 276.1553; found: 276.1539.

Methyl 5-(4,4,6-Trimethyl-1,3,2-dioxaborinan-2-yl)-1*H*-pyrrole-2-carboxylate (8a)
Colorless oil; yield: 236 mg (94%).

^1H NMR (600 MHz, $CDCl_3$): δ = 9.43 (s, 1 H), 6.87 (d, *J* = 3.5, 1 H), 6.65 (d, *J* = 3.5, 1 H), 4.31 (dqd, *J* = 12.2, 6.1, 2.9 Hz, 1 H), 3.85 (s, 3 H), 1.85 (dd, *J* = 14.0, 2.8 Hz, 1 H), 1.65–1.51 (m, 1 H), 1.35 (s, 3 H), 1.34 (s, 3 H), 1.32 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 161.52, 125.23, 118.55, 115.49, 71.46, 65.21, 51.39, 46.05, 31.11, 28.01, 23.04.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{12}H_{18}BNO_4$: 251.1329; found: 251.1328.

Methyl 5-(4,4,6-Trimethyl-1,3,2-dioxaborinan-2-yl)furan-2-carboxylate (8b)
White solid; yield: 211 mg (92%); isomeric mixture 91:9.

^1H NMR (600 MHz, $CDCl_3$): δ = 7.15 (d, *J* = 3.4 Hz, 1 H), 6.95 (d, *J* = 3.5 Hz, 1 H), 4.34 (dqd, *J* = 12.2, 6.2, 2.9 Hz, 1 H), 3.88 (s, 3 H), 1.86 (dd, *J* = 14.0, 2.9 Hz, 1 H), 1.68–1.55 (m, 1 H), 1.37 (s, 3 H), 1.36 (s, 3 H), 1.34 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 159.32, 147.39, 121.97, 118.01, 71.94, 65.59, 51.81, 46.05, 30.96, 28.01, 22.93.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{12}H_{17}BO_5$: 252.1169; found: 252.1176.

2-(4,4,6-Trimethyl-1,3,2-dioxaborinan-2-yl)-1*H*-indole (8c)
White solid; yield: 226 mg (93%).

^1H NMR (600 MHz, $CDCl_3$): δ = 8.54 (s, 1 H), 7.66 (d, *J* = 7.8 Hz, 1 H), 7.39 (d, *J* = 8.2 Hz, 1 H), 7.20 (t, *J* = 7.5 Hz, 1 H), 7.07 (dd, *J* = 14.9, 7.2 Hz, 1 H), 7.02 (s, 1 H), 4.42–4.34 (m, 1 H), 1.89 (dd, *J* = 13.9, 2.7 Hz, 1 H), 1.68–1.62 (m, 1 H), 1.41 (s, 3 H), 1.40 (s, 3 H), 1.37 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 137.79, 128.65, 122.81, 121.32, 119.35, 111.50, 111.08, 71.45, 65.23, 46.12, 31.21, 28.12, 23.14.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{14}H_{18}BNO_2$: 243.1431; found: 243.1438.

2-(Benzofuran-2-yl)-4,4,6-trimethyl-1,3,2-dioxaborinane (8d)
White solid; yield: 231 mg (94%).

^1H NMR (600 MHz, $CDCl_3$): δ = 7.60 (d, *J* = 7.7 Hz, 1 H), 7.56 (d, *J* = 8.3 Hz, 1 H), 7.32–7.28 (m, 2 overlapping peaks, 2 H), 7.20 (t, *J* = 7.4 Hz, 1 H), 4.41 (dqd, *J* = 12.3, 6.2, 2.9 Hz, 1 H), 1.91 (dd, *J* = 14.0, 2.9 Hz, 1 H), 1.68 (dd, *J* = 12.0, 1 H), 1.43 (s, 3 H), 1.42 (s, 3 H), 1.40 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 157.28, 127.86, 125.13, 122.35, 121.52, 117.49, 111.90, 71.94, 65.60, 46.12, 31.06, 28.05, 23.03.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{14}H_{17}BO_3$: 244.1271; found: 244.1277.

2-(Benzo[*b*]thiophen-2-yl)-4,4,6-trimethyl-1,3,2-dioxaborinane (8e)
Colorless oil; yield: 135 mg (52%).

^1H NMR (600 MHz, $CDCl_3$): δ = 7.91 (m, 1 H), 7.88–7.82 (2 overlapping peaks, 2 H), 7.38–7.33 (2 overlapping peaks, 2 H), 4.41 (dqd, *J* = 12.3, 6.2, 2.9 Hz, 1 H), 1.89 (dd, *J* = 14.0, 2.9 Hz, 1 H), 1.67 (m, 1 H), 1.43 (s, 3 H), 1.42 (s, 3 H), 1.39 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 143.50, 140.86, 132.45, 124.79, 124.17, 123.91, 122.56, 71.87, 65.64, 46.13, 31.26, 28.20, 23.20.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{14}H_{17}BO_2S$: 260.1042; found: 260.1042.

2,6-Dichloro-4-(4,4,6-trimethyl-1,3,2-dioxaborinan-2-yl)pyridine (8f)
White solid; yield: 203 mg (74%).

^1H NMR (600 MHz, $CDCl_3$): δ = 7.56 (s, 2 H), 4.35 (dqd, *J* = 12.3, 6.2, 2.9 Hz, 1 H), 1.91 (dd, *J* = 14.1, 2.9 Hz, 1 H), 1.59 (t, *J* = 12.8 Hz, 1 H), 1.38 (s, 3 H), 1.36 (s, 3 H), 1.34 (d, *J* = 6.2 Hz, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 150.04, 127.12, 72.28, 65.82, 45.79, 30.93, 28.05, 22.85.

HRMS (EI): *m*/*z* $[M]^+$ calcd for $C_{11}H_{14}BCl_2NO_2$: 273.0495; found: 273.0487.

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Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synthesis.

References

(1) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457.
(2) Qiao, J. X.; Lam, P. Y. S. *Synthesis* **2011**, 829.
(3) Ishiyama, T.; Miyaura, N. *J. Organomet. Chem.* **2000**, *611*, 392.
(4) Cho, J. Y.; Tse, M. K.; Holmes, D.; Maleczka, R. E.; Smith, M. R. *Science (Washington, D.C.)* **2002**, *295*, 305.
(5) Ishiyama, T.; Takagi, J.; Ishida, K.; Miyaura, N.; Anastasi, N. R.; Hartwig, J. F. *J. Am. Chem. Soc.* **2002**, *124*, 390.
(6) Mkhalid, I. A. I.; Barnard, J. H.; Marder, T. B.; Murphy, J. M.; Hartwig, J. F. *Chem. Rev.* **2010**, *110*, 890.
(7) Hartwig, J. F. *Chem. Soc. Rev.* **2011**, *40*, 1992.
(8) Engle, K. M.; Mei, T. S.; Wasa, M.; Yu, J. Q. *Acc. Chem. Res.* **2012**, *45*, 788.
(9) Lyons, T. W.; Sanford, M. S. *Chem. Rev.* **2010**, *110*, 1147.
(10) Colby, D. A.; Bergman, R. G.; Ellman, J. A. *Chem. Rev.* **2010**, *110*, 624.
(11) Iwadate, N.; Suginome, M. *J. Organomet. Chem.* **2009**, *694*, 1713.
(12) Liskey, C. W.; Wei, C. S.; Pahls, D. R.; Hartwig, J. F. *Chem. Commun.* **2009**, 5603.
(13) Boller, T. M.; Murphy, J. M.; Hapke, M.; Ishiyama, T.; Miyaura, N.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 14263.
(14) Tzschucke, C. C.; Murphy, J. M.; Hartwig, J. F. *Org. Lett.* **2007**, *9*, 761.
(15) Murphy, J. M.; Tzschucke, C. C.; Hartwig, J. F. *Org. Lett.* **2007**, *9*, 757.

(16) Carrow, B. P.; Hartwig, J. F. *J. Am. Chem. Soc.* **2011**, *133*, 2116.
(17) Myslinska, M.; Heise, G. L.; Walsh, D. J. *Tetrahedron Lett.* **2012**, *53*, 2937.
(18) Murata, M.; Oda, T.; Watanabe, S.; Masuda, Y. *Synthesis* **2007**, 351.
(19) PraveenGanesh, N.; Chavant, P. Y. *Eur. J. Org. Chem.* **2008**, 4690.
(20) Hexylene glycol: $0.014/g; pinacol: 0.705/g; cost of reagents determined by the largest amount commercially available from http://www.aldrich.com (April 2013).

