ACS Catalysis

Letter

pubs.acs.org/acscatalysis

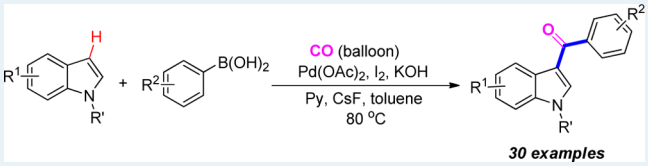
Palladium-Catalyzed Carbonylation of Indoles for Synthesis of Indol-3-yl Aryl Ketones

Mi-Na Zhao, Longfei Ran, Ming Chen, Zhi-Hui Ren, Yao-Yu Wang, and Zheng-Hui Guan*

Key Laboratory of Synthetic and Natural Functional Molecule Chemistry of Ministry of Education, Department of Chemistry & Materials Science, Northwest University, Xi'an 710127, P. R. China

Supporting Information

ABSTRACT: A novel palladium-catalyzed carbonylation of indoles with CO and aromatic boronic acids for the synthesis of indol-3-yl aryl ketones was developed. The reaction tolerates a wide range of functional groups and gives a variety of valuable indol-3-yl aryl ketones in high yields under mild conditions.



KEYWORDS: *palladium-catalyzed, carbonylation, indoles, arylboronic acids, indol-3-yl aryl ketones*

Transition-metal-catalyzed carbonylation with CO is one of the fundamental reactions in both scientific research and chemical industries.[1] Especially, transition-metal-catalyzed carbonylation of C−H bonds has been developed as promising protocols for the construction of carbonyl compounds. The pioneering work of Pd-catalyzed oxidative carbonylation of aryl C−H bonds for synthesis of aromatic carboxylic acids,[2] Ru- or Rh-catalyzed reductive carbonylation of aryl C−H bonds for synthesis of aryl ethyl ketones has been developed in the past decades.[3] Recently, Pd, Ru, or Rh-catalyzed oxidative carbonylation of C−H bonds for the construction of esters,[4] lactones,[5] lactams,[6] and anhydrides[7] have been developed by several groups including ours.[4g,5a,7] However, most of these reactions employ water, alcohols, or amines as the coupling partners.[8] Transition-metal-catalyzed carbonylation of aromatic C−H bonds with CO and organic boronic acids for direct synthesis of diaryl ketones has not yet been realized.

Aromatic boronic acids are commercially available reagents and have been widely used in Suzuki−Miyaura coupling reactions.[9] Carbonylation of aromatic C−H bonds with CO and aromatic boronic acids would not only open a straightforward route to versatile unsymmetric diaryl ketones but also extend the scope of transition-metal-catalyzed C−H bonds carbonylations. Indoles which are capable of binding to many receptors with high affinity have been recognized as "privileged structures" in drug discovery.[10] Particularly, indol-3-yl aryl ketones have been found to exhibit good biological and pharmaceutical activities, such as anticancer, antiemetic, analgesic, and anti-HIV-1.[11] In this paper, we describe the development of a novel Pd-catalyzed carbonylation of indoles with CO and aromatic boronic acids for the synthesis of indol-3-yl aryl ketones under mild conditions.

We began our study with the Pd-catalyzed carbonylation of *N*-methylindole **1a** with CO and phenylboronic acid **2a**. In an initial attempt, a set of experiments were carried out using $Cu(OAc)_2$, $PhI(OAc)_2$, or $K_2S_2O_8$ as the oxidant in the presence of $Pd(OAc)_2$ catalyst. However, no reaction was observed. Recently, tandem C−H bond iodination/cross-coupling reaction has been developed as an efficient strategy for the C−H bond transformations.[12] Inspired by these elegant works, iodine was employed as the oxidant in our carbonylation reaction. Gratifyingly, the target product **3aa** was obtained in 28% yield when 1.2 equiv of iodine was added in the reaction (Table 1, entry 1). Then, much effort, such as screening different solvents and bases, and optimizing the palladium precursors, has been devoted to improving the reaction efficiency (Table 1, entries 2−11). However, only slightly improved yield (45%) was obtained when KOH was employed as the base (Table 1, entry 8).

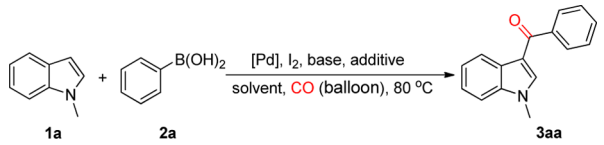
To develop a reliable method for Pd-catalyzed carbonylation of indoles with CO and aromatic boronic acids, we then turned our attention to screening of various additives (Table 1, entries 12−14). Pyridine was found to be an effective additive in the reaction (Table 1, entry 14).[13] Furthermore, fluoride salts which could activate the boronic acid to accelerate the transmetalation step in Suzuki couplings were also screened (Table 1, entries 15−17).[9] It was found that the significantly improved reaction yield (78%) was obtained by using pyridine and CsF as the additives (Table 1, entry 17). However, only a trace amount of the product **3aa** was observed when potassium phenyltrifluoroborate instead of phenyl boronic acid **2a** was used in the reaction. In addition, 17% yield of **3aa** was obtained when phenylboronic acid pinacol ester was used as the substrate.

With the optimized reaction conditions established, a series of aromatic boronic acids were investigated for extending the substrate scope (Table 2). This new carbonylation reaction displayed high functional-group tolerance and proved to be a general method for the preparation of indol-3-yl aryl ketones. Aromatic boronic acids bearing electron-donating groups, such

Received: December 1, 2014
Revised: January 15, 2015
Published: January 20, 2015

DOI: 10.1021/cs5019106
ACS Catal. 2015, 5, 1210−1213

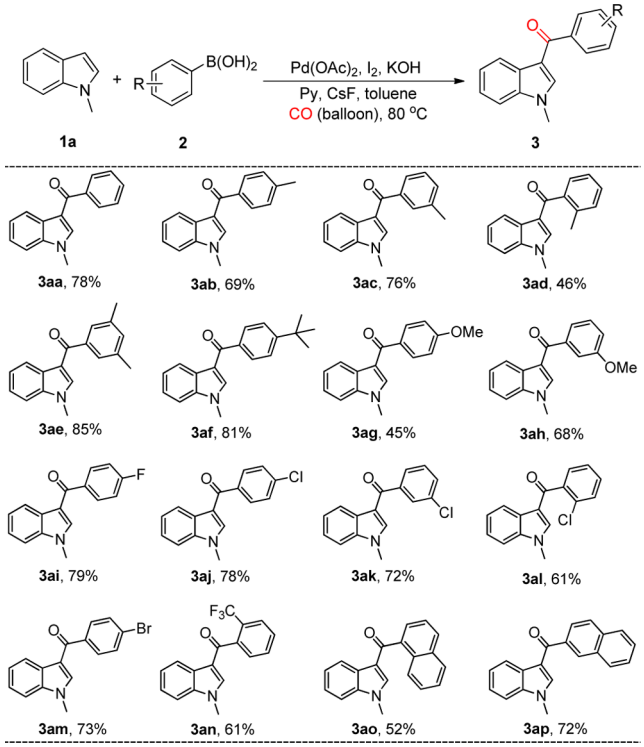
Table 1. Optimization of the Reaction Conditions[a]



entry	catalyst	base	additive	solvent	yield (%)
1	$Pd(OAc)_2$	K_2CO_3		toluene	28
2	$Pd(OAc)_2$	K_2CO_3		MeCN	0
3	$Pd(OAc)_2$	K_2CO_3		DMF	15
4	$Pd(OAc)_2$	K_2CO_3		DMSO	10
5	$Pd(OAc)_2$	K_3PO_4		toluene	15
6	$Pd(OAc)_2$	Cs_2CO_3		toluene	30
7	$Pd(OAc)_2$	*t*-BuOK		toluene	24
8	$Pd(OAc)_2$	KOH		toluene	45
9	$PdCl_2$	KOH		toluene	30
10	$Pd(PPh_3)_2Cl_2$	KOH		toluene	25
11	$Pd(dba)_2$	KOH		toluene	32
12	$Pd(OAc)_2$	KOH	TMEDA	toluene	12
13	$Pd(OAc)_2$	KOH	NEt_3	toluene	20
14[b]	$Pd(OAc)_2$	KOH	Py	toluene	60
15[b,c]	$Pd(OAc)_2$	KOH	Py, KF	toluene	62
16[b,c]	$Pd(OAc)_2$	KOH	Py, AgF	toluene	64
17[b,c]	$Pd(OAc)_2$	KOH	Py, CsF	toluene	78

[a]Reaction condition: **1a** (0.2 mmol), **2a** (0.24 mmol), $Pd(OAc)_2$ (5 mol %), I_2 (1.2 equiv), base (3 equiv), solvent (3 mL); isolated yields. [b]1.0 equiv of pyridine was added. [c]1.5 equiv of MF was added.

Table 2. Palladium-Catalyzed Carbonylation of *N*-Methylindole 1a with Arylboronic Acids[a]

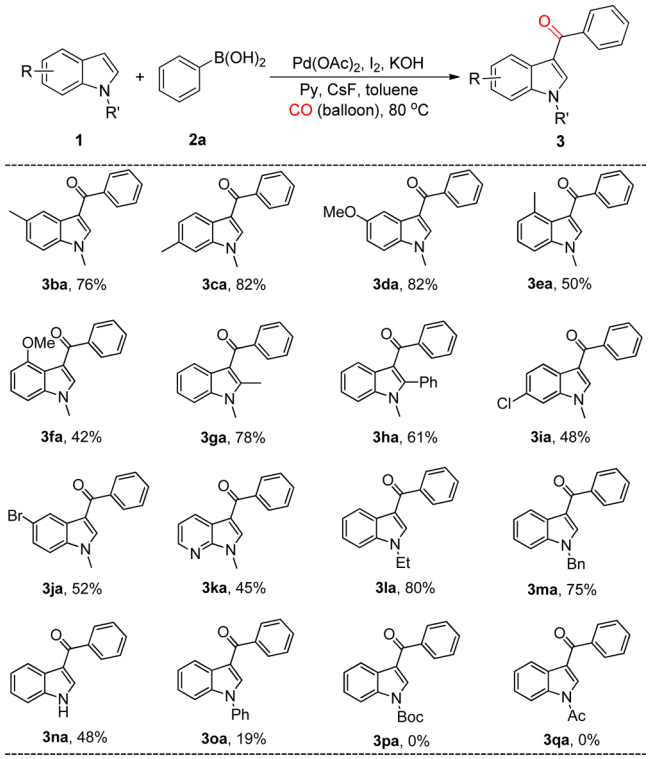


[a]Reaction conditions: **1a** (0.2 mmol), **2** (1.2 equiv), $Pd(OAc)_2$ (5 mol %), iodine (1.2 equiv), KOH (3.0 equiv), pyridine (1.0 equiv), and CsF (1.5 equiv) in toluene (3 mL) under CO (balloon) at 80 °C; isolated yields.

as methyl, dimethyl, *tert*-butyl, and methoxyl, proceeded smoothly in the reaction to give the corresponding indol-3-yl aryl ketones **3aa**−**3ah** in good yields. Because the carbonylations are generally sensitive to steric features of the substrates,[4f,5a,7,14] *o*-tolylboronic acid **2d** resulted in moderate conversion and 46% yield of the product **3ad**. But the reason for the low yield of **3ag** was the side homocarbonylation of (4-methoxyphenyl)boronic acid **2g** and CO (30% of bis(4-methoxyphenyl)methanone was isolated).[15] Electron-withdrawing-group-substituted aromatic boronic acids, such as **2i**−**2n**, were also well tolerated in the reaction to afford the corresponding indol-3-yl aryl ketones **3ai**−**3an** in 61−79% yields. These results indicate that the electronic nature of the aromatic boronic acids has little influence on the carbonylation reaction. Notably, indol-3-yl naphthyl ketones (cannabimimetic indoles) are high affinity binding to the cannabinoid CB1 and CB2 receptors. Our carbonylation reaction allowed the synthesis of cannabimimetic indole (JWH-070) **3ao** in 52% yield directly.[11d] However, only a trace of the desired product was obtained when phenethylboronic acid, *β*-styreneboronic acid, or 2-thienylboronic acid was used as the substrate.

Next, various indoles were investigated for further extending the substrate scope (Table 3). *N*-Methylindoles bearing electron-donating groups, such as methyl and methoxyl, proceeded smoothly in the reaction to give the desired substituted indol-3-yl phenyl ketones **3ba**−**3da** in high yields. 2-Methyl or 2-phenyl-substituted indoles **1g**−**1h** produced the corresponding indol-3-yl phenyl ketones **3ga**−**3ha** in good yields. However, 4-methyl- or 4-methoxyl-substituted *N*-

Table 3. Palladium-Catalyzed Carbonylation of Phenylboronic Acid 2a with Indoles[a]



[a]Reaction conditions: **1** (0.2 mmol), **2a** (1.2 equiv), $Pd(OAc)_2$ (5 mol %), iodine (1.2 equiv), KOH (3.0 equiv), pyridine (1.0 equiv), and CsF (1.5 equiv) in toluene (3 mL) under CO (balloon) at 80 °C; isolated yields.

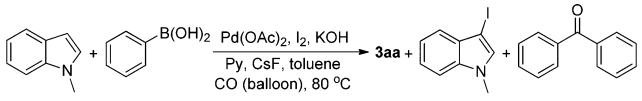
DOI: 10.1021/cs5019106
ACS Catal. 2015, 5, 1210−1213

methylindoles **1e**−**1f** gave the desired indol-3-yl phenyl ketones **3ea**−**3fa** in only moderate yields. These results reveal that the steric features of the 4-position (other than 2-position) of the indoles plays a role in the carbonylation reaction.[4f,5a,7,14]

Electron-withdrawing-group-substituted indoles, such as **1i**−**1j** and 7-azaindole **1k**, were less reactive in the reaction (*moderate conversions*).[4f] Therefore, the desired indol-3-yl phenyl ketones **3ia**−**3ka** were obtained in 45−52% yields. Furthermore, indoles with a different substituent on the nitrogen atom were investigated. *N*-Ethylindole **1l** and *N*-benzylindole **1m** were well tolerated in the carbonylation. Free *NH*-indole **1n** could also be used as a substrate to produce 3-benzoyl indole **3na** in 48% yield. However, *N*-phenyl 3-benzoyl indole **3oa** was obtained in only 19% yield, with 52% recovery of the *N*-phenyl indole **1o**. Furthermore, no reaction occurred when *N*-Boc-indole **1p** or *N*-acetyl-indole **1q** was employed as the substrate.

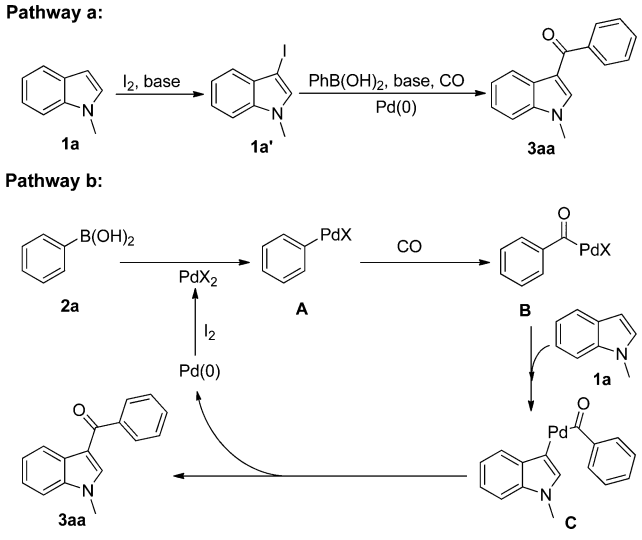
To gain insight into the mechanism of the reaction, experiments were carried out under the standard conditions (Scheme 1). The 3-iodo-1-methyl-indole **1a′** was obtained in

Scheme 1. Control Experiments



62% yield when the reaction was performed in the absence of phenylboronic acid **2a**. However, in the absence of indole **1a**, the benzophenone **4** was formed in 49% yield. These results indicate that two pathways were possible for this carbonylation. In one case, iodination of indole sequential with Pd(0)-catalyzed carbonylation of 3-iodo-indole **1a′** and phenyboronic acid **2a** in the presence of CO gives the final indol-3-yl phenyl ketone **3aa** (Scheme 2, pathway a).[16] Alternatively, transmetalation of phenylboronic acid **2a** with Pd(II) followed by CO insertion generates a benzoylpalladium intermediate **B**.[15] Then, palladation of C−H bond of indole **1a** sequential with

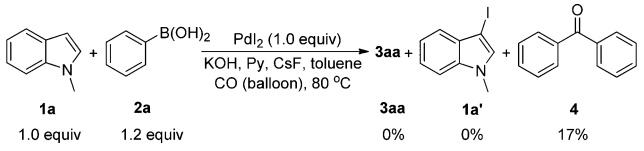
Scheme 2. Proposed Mechanisms



reductive elimination of intermediate **C** produces the indol-3-yl phenyl ketone **3aa** (Scheme 2, pathway b).

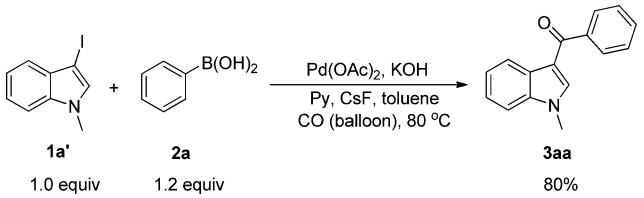
In the pathway b, iodine should act as an oxidant to regenerate the Pd(II) catalyst. If the reaction is proceeded through pathway b, the indol-3-yl phenyl ketone **3aa** should be observed when stoichiometric PdI_2 (or $PdI_2(MeCN)_2$) instead of catalytic $Pd(OAc)_2$ and stoichiometric iodine. However, the indol-3-yl phenyl ketone **3aa** was not observed either in the presence of stoichiometric PdI_2 or $PdI_2(MeCN)_2$ (Scheme 3). This observation indicates that the pathway b is less likely.

Scheme 3. Reaction Using Stoichiometric PdI_2 as the Catalyst



To further confirm the pathway a, 3-iodo-1-methyl-indole **1a′** was reacted with phenylboronic acid **2a** under the standard conditions (Scheme 4). The desired indol-3-yl phenyl ketone **3aa** was obtained in 80% yield. This result indicates that the pathway a is more likely for this carbonylation.

Scheme 4. Carbonylation of 3-Iodo-1-methyl-indole



In summary, a novel palladium-catalyzed carbonylation of indoles with CO and aromatic boronic acids for the synthesis of indol-3-yl aryl ketones has been developed. The reaction employs readily available indoles and aromatic boronic acids as the substrates and tolerates a wide range of functional groups. A series of valuable indol-3-yl aryl ketones were easily synthesized in high yields under mild conditions. Further scope of the reaction is underway.

EXPERIMENTAL SECTION

General Procedure for Carbonylation of Indoles with Arylboronic Acids. Indoles **1** (0.2 mmol), aryboronic acids **2** (0.24 mmol), $Pd(OAc)_2$ (5 mol %, 2.2 mg), I_2 (2.4 mmol, 60 mg), KOH (0.6 mmol, 33.6 mg), pyridine (0.2 mmol, 15.8 mg), CsF (0.3 mmol, 45 mg), and toluene (3 mL) was charged in a 10 mL round-bottom flask. Then, the flask was evacuated and backfilled with CO (3 times, balloon) and stirred under CO (balloon) at 80 °C for 12 h. When the reaction was completed (detected by TLC), the mixture was cooled to room temperature and carefully vented to discharge the excess CO. The reaction was quenched with H_2O (10 mL) and extracted with EtOAc (3 × 10 mL). The combined organic layers were dried over anhydrous Na_2SO_4 and then evaporated in vacuo. The residue was purified by column chromatography on silica gel to afford the corresponding indol-3-yl aryl ketones **3** with hexanes/ethyl acetate (5:1 to 3:1) as the eluent.

DOI: 10.1021/cs5019106
ACS Catal. 2015, 5, 1210−1213

■ ASSOCIATED CONTENT

Supporting Information

The following file is available free of charge on the ACS Publications website at DOI: 10.1021/cs5019106.

Detailed experimental procedures, characterization data, and copies of NMR spectra for all product (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: guanzhh@nwu.edu.cn.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by generous grants from the National Natural Science Foundation of China (21472147, 21272183) and the Fund of the Rising Stars of Shanxi Province (2012KJXX-26).

■ REFERENCES

(1) (a) Sumino, S.; Fusano, A.; Fukuyama, T.; Ryu, I. *Acc. Chem. Res.* **2014**, *47*, 1563−1574. (b) Wu, X.-F.; Neumann, H.; Beller, M. *Chem. Rev.* **2013**, *113*, 1−35. (c) Franke, R.; Selent, D.; Börner, A. *Chem. Rev.* **2012**, *112*, 5675−5732. (d) Liu, Q.; Zhang, H.; Lei, A. *Angew. Chem., Int. Ed.* **2011**, *50*, 10788−10799. (e) Wu, X.-F.; Neumann, H.; Beller, M. *Chem. Soc. Rev.* **2011**, *40*, 4986−5009.

(2) (a) Giri, R.; Lam, J. K.; Yu, J.-Q. *J. Am. Chem. Soc.* **2010**, *132*, 686−693. (b) Giri, R.; Yu, J.-Q. *J. Am. Chem. Soc.* **2008**, *130*, 14082−14083. (c) Ohashi, S.; Sakaguchi, S.; Ishii, Y. *Chem. Commun.* **2005**, 486−488. (d) Jia, C.; Kitamura, T.; Fujiwara, Y. *Acc. Chem. Res.* **2001**, *34*, 633−639. (e) Fujiwara, Y.; Kawanchi, T.; Taniguchi, H. *J. Chem. Soc., Chem. Commun.* **1980**, 220−221.

(3) (a) Chatani, N.; Asaumi, T.; Ikeda, T.; Yorimitsu, S.; Ishii, Y.; Kakiuchi, F.; Murai, S. *J. Am. Chem. Soc.* **2000**, *122*, 12882−12883. (b) Fukuyama, T.; Chatani, N.; Tatsumi, J.; Kakiuchi, F.; Murai, S. *J. Am. Chem. Soc.* **1998**, *120*, 11522−11523. (c) Chatani, N.; Fukuyama, T.; Kakiuchi, F.; Murai, S. *J. Am. Chem. Soc.* **1996**, *118*, 493−494. (d) Moore, E. J.; Pretzer, W. R.; Oconnell, T. J.; Harris, J.; Labounty, L.; Chou, L.; Grimmer, S. S. *J. Am. Chem. Soc.* **1992**, *114*, 5888−5890.

(4) (a) Xie, P.; Xie, Y.; Qian, B.; Zhou, H.; Xia, C.; Huang, H. *J. Am. Chem. Soc.* **2012**, *134*, 9902−9905. (b) Lang, R.; Shi, L.; Li, D.; Xia, C.; Li, F. *Org. Lett.* **2012**, *14*, 4130−4133. (c) Lang, R.; Wu, J.; Shi, L.; Xia, C.; Li, F. *Chem. Commun.* **2011**, *47*, 12553−12555. (d) Zhang, H.; Liu, D.; Chen, C.; Liu, C.; Lei, A. *Chem.—Eur. J.* **2011**, *17*, 9581−9585. (e) Li, H.; Cai, G.-X.; Shi, Z.-J. *Dalton Trans.* **2010**, *39*, 10442−10446. (f) Houlden, C. E.; Hutchby, M.; Bailey, C. D.; Ford, J. G.; Tyler, S. N. G.; Gagné, M. R.; Lloyd-Jones, G. C.; Booker-Milburn, K. I. *Angew. Chem., Int. Ed.* **2009**, *48*, 1830−1833. (g) Guan, Z.-H.; Ren, Z.-H.; Spinella, S. M.; Yu, S.; Liang, Y.-M.; Zhang, X. *J. Am. Chem. Soc.* **2009**, *131*, 729−733.

(5) (a) Chen, M.; Ren, Z.-H.; Wang, Y.-Y.; Guan, Z.-H. *Angew. Chem., Int. Ed.* **2013**, *52*, 14196−14199. (b) Luo, S.; Luo, F.-X.; Zhang, X.-S.; Shi, Z.-J. *Angew. Chem., Int. Ed.* **2013**, *52*, 10598−10601. (c) Inamoto, K.; Kadokawa, J.; Kondo, Y. *Org. Lett.* **2013**, *15*, 3962−3965. (d) Ferguson, J.; Zeng, F.; Alper, H. *Org. Lett.* **2012**, *14*, 5602−5605. (e) Lu, Y.; Leow, D.; Wang, X.; Engle, K. M.; Yu, J.-Q. *Chem. Sci.* **2011**, *2*, 967−971.

(6) (a) Li, S.; Chen, G.; Feng, C.-G.; Gong, W.; Yu, J.-Q. *J. Am. Chem. Soc.* **2014**, *136*, 5267−5270. (b) Li, W.; Liu, C.; Zhang, H.; Ye, K.; Zhang, G.; Zhang, W.; Duan, Z.; You, S.; Lei, A. *Angew. Chem., Int. Ed.* **2014**, *53*, 2443−2446. (c) Liang, D.; He, Y.; Zhu, Q. *Org. Lett.* **2014**, *16*, 2748−2751. (d) Xie, P.; Xia, C.; Huang, H. *Org. Lett.* **2013**, *15*, 3370−3373. (e) Yoo, E. J.; Wasa, M.; Yu, J.-Q. *J. Am. Chem. Soc.* **2010**, *132*, 17378−17380. (f) Hasegawa, N.; Charra, V.; Inoue, S.; Fukumoto, Y.; Chatani, N. *J. Am. Chem. Soc.* **2011**, *133*, 8070−8073. (g) Inoue, S.; Shiota, H.; Fukumoto, Y.; Chatani, N. *J. Am. Chem. Soc.* **2009**, *131*, 6898−6899. (h) Haffemayer, B.; Gulias, M.; Gaunt, M. J. *Chem. Sci.* **2011**, *2*, 312−315. (i) López, B.; Rodriguez, A.; Santos, D.; Albert, J.; Ariza, X.; Garcia, J.; Granell, J. *Chem. Commun.* **2011**, *47*, 1054−1056. (j) Ma, B.; Wang, Y.; Peng, J.; Zhu, Q. *J. Org. Chem.* **2011**, *76*, 6362−6366. (k) Orito, K.; Horibata, A.; Nakamura, T.; Ushito, H.; Nagasaki, H.; Yuguchi, M.; Yamashita, S.; Tokuda, M. *J. Am. Chem. Soc.* **2004**, *126*, 14342−14343.

(7) Guan, Z.-H.; Chen, M.; Ren, Z.-H. *J. Am. Chem. Soc.* **2012**, *134*, 17490−17493.

(8) (a) Fang, X.; Li, H.; Jackstell, R.; Beller, M. *Angew. Chem., Int. Ed.* **2014**, *53*, 9030−9034. (b) Shin, S.; Jeong, Y.; Jeon, W. H.; Lee, P. H. *Org. Lett.* **2014**, *16*, 2930−2933. (c) Tlili, A.; Schranck, J.; Pospech, J.; Neumann, H.; Beller, M. *Angew. Chem., Int. Ed.* **2013**, *52*, 6293−6297. (d) Zhang, H.; Shi, R.; Gan, P.; Liu, C.; Ding, A.; Wang, Q.; Lei, A. *Angew. Chem., Int. Ed.* **2012**, *51*, 5204−5207. (e) Wu, X.-F.; Anbarasan, P.; Neumann, H.; Beller, M. *Angew. Chem., Int. Ed.* **2010**, *49*, 7316−7319. (f) Zhang, Z.; Liu, Y.; Ling, L.; Li, Y.; Dong, Y.; Gong, M.; Zhao, X.; Zhang, Y.; Wang, J. *J. Am. Chem. Soc.* **2011**, *133*, 4330−4341.

(9) (a) Suzuki, A. *Angew. Chem., Int. Ed.* **2011**, *50*, 6722−6737. (b) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457−2483. (c) Suzuki, A. *Acc. Chem. Res.* **1982**, *15*, 178−184. (d) Partyka, D. V. *Chem. Rev.* **2011**, *111*, 1529−1595. (e) Yang, S.-D.; Sun, C.-L.; Fang, Z.; Li, B.-J.; Li, Y.-Z.; Shi, Z.-J. *Angew. Chem., Int. Ed.* **2008**, *47*, 1473−1476. (f) Wang, D.-H.; Wasa, M.; Giri, R.; Yu, J.-Q. *J. Am. Chem. Soc.* **2008**, *130*, 7190−7191.

(10) (a) Cacchi, S.; Fabrizi, G. *Chem. Rev.* **2011**, *111*, 215−283. (b) Humphrey, G. R.; Kuethe, J. T. *Chem. Rev.* **2006**, *106*, 2875−2911. (c) Lebrasseur, N.; Larrosa, I. In *Advances in Heterocyclic Chemistry*; Katritzky, A. R., Ed.; Academic Press: San Diego, CA, 2012; Vol. *105*, pp 309−351.

(11) (a) Vasiljevik, T.; Franks, L. N.; Ford, B. M.; Douglas, J. T.; Prather, P. L.; Fantegrossi, W. E.; Prisinzano, T. E. *J. Med. Chem.* **2013**, *56*, 4537−4550. (b) Barreca, M. L.; Ferro, S.; Rao, A.; Luca, L. D.; Zappala, M.; Monforte, A.-M.; Debyser, Z.; Witvrouw, M.; Chimirri, A. *J. Med. Chem.* **2005**, *48*, 7084−7088. (c) Kuo, C.-C.; Hsieh, H.-P.; Pan, W.-Y.; Chen, C.-P.; Liou, J.-P.; Lee, S.-J.; Chang, Y.-L.; Chen, L.-T.; Chen, C.-T.; Chang, J.-Y. *Cancer Res.* **2004**, *64*, 4621−4628. (d) Aung, M. M.; Griffin, G.; Huffman, J. W.; Wu, M.-J.; Keel, C.; Yang, B.; Showalter, V. M.; Abood, M. E.; Martin, B. R. *Drug Alcohol Depen.* **2000**, *60*, 133−140. (e) Ohta, M.; Suzuki, T.; Furuya, T.; Kurihara, H.; Tokunaga, T.; Miyata, K.; Yanagisawa, I. *Chem. Pharm. Bull.* **1996**, *44*, 1707−1716.

(12) (a) Do, H.-Q.; Daugulis, O. *J. Am. Chem. Soc.* **2011**, *133*, 13577−13586. (b) Li, J.-J.; Mei, T.-S.; Yu, J.-Q. *Angew. Chem., Int. Ed.* **2008**, *47*, 6452−6455.

(13) (a) Pyridine may play a role in the C-H bond iodination step, see ref 12a;. (b) Wang, Z.; Song, F.; Zhao, Y.; Huang, Y.; Yang, L.; Zhao, D.; Lan, J.; You, J. *Chem.—Eur. J.* **2012**, *18*, 16616−16620.

(14) Barnard, C. F. J. *Organometallics* **2008**, *27*, 5402−5422.

(15) (a) Ren, L.; Jiao, N. *Chem.—Asian J.* **2014**, *9*, 2411−2414. (b) Lu, W.; Li, Y.; Wang, C.; Xue, D.; Chen, J.-G.; Xiao, J. *Org. Biomol. Chem.* **2014**, *12*, 5243−5249. (c) Wu, X.-F.; Neumann, H.; Beller, M. *Chem. Asian. J.* **2012**, *7*, 282−285. (d) Liu, Q.; Li, G.; He, J.; Liu, J.; Li, P.; Lei, A. *Angew. Chem., Int. Ed.* **2010**, *49*, 3371−3374.

(16) (a) Burhardt, M. N.; Taaning, R. H.; Skrydstrup, T. *Org. Lett.* **2013**, *15*, 948−951. (b) Friis, S. D.; Andersen, T. L.; Skrydstrup, T. *Org. Lett.* **2013**, *15*, 1378−1381. (c) Ho, S.; Bondarenko, G.; Rosa, D.; Dragisic, B.; Orellana, A. *J. Org. Chem.* **2012**, *77*, 2008−2012. (d) Friis, S. D.; Taaning, R. H.; Lindhardt, A. T.; Skrydstrup, T. *J. Am. Chem. Soc.* **2011**, *133*, 18114−18117. (e) Nishiyama, T.; Choshi, T.; Kitano, K.; Hibino, S. *Tetrahedron Lett.* **2011**, *52*, 3876−3878. (f) Karpov, A. S.; Merkul, E.; Rominger, F.; Müller, T. J. J. *Angew. Chem., Int. Ed.* **2005**, *44*, 6951−6956. (g) Campo, M. A.; Larock, R. C. *J. Org. Chem.* **2002**, *67*, 5616−5620. (h) Liu, Y.; Gribble, G. W. *Tetrahedron Lett.* **2001**, *42*, 2949−2951.

DOI: 10.1021/cs5019106
ACS Catal. 2015, 5, 1210−1213