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Rh(III)-Catalyzed Regioselective Functionalization of C−H Bonds of Naphthylcarbamates for Oxidative Annulation with Alkynes

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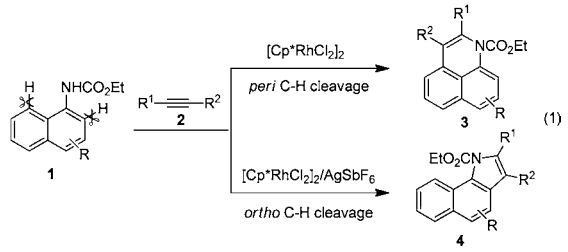
Supporting Information

ABSTRACT: A Rh(III)-catalyzed highly efficient and regioselective functionalization of diverse C−H bonds of naphthylcarbamates for oxidative annulation with alkynes has been developed. The annulation with a neutral rhodium catalyst system proceeds through *peri* C−H bond functionalization of arylcarbamates to give benzoquinoline derivatives, while with a cationic rhodium catalyst system it proceeds through *ortho* C−H functionalization of arylcarbamates to furnish benzoindole derivatives.

Metal-catalyzed direct aromatic C−H activation/annulation reactions have become the conceptually important synthetic strategy for the construction of diverse π-conjugated polycycles in the field of synthetic chemistry and functional materials.[1,2] Among them, oxidative annulations of acetanilides, benzamides, and their analogues with alkynes via C−H/N−H functionalization using various Rh, Pd, Ni, and Ru catalysts have attracted particular interest because they enable the synthesis of useful heteroarenes such as indoles, isoquinolones, isoquinolines, and pyrroles without prefunctionalization of *ortho*-aromatic C−H bonds.[2−7]

One important challenge of these reactions is selective annulation of alkynes with molecules bearing more than one type of cleavable C−H bonds,[8] which would assemble interesting polyheterocycles via regioselective C−H functionalization. Herein, we describe a Rh(III)-catalyzed highly efficient and regioselective functionalization of diverse C−H bonds for oxidative annulation of naphthylcarbamates with alkynes (eq 1). The *peri* C−H bond of arylcarbamates (**1**) was cleaved by the



neutral Rh(III) catalyst system to give the corresponding benzoquinoline derivatives (**3**), while the *ortho* C−H bond was cleaved in the presence of a cationic Rh(III) catalyst system to afford the corresponding benzoindole derivatives (**4**). To our knowledge, the intermolecular *peri* C−H/N−H annulation of naphthylanilides with alkynes has remained unexplored.

It was reported that the oxidative C−H/O−H annulation of 1-naphthols with alkynes produced fused pyran derivatives through regioselective cleavage of the *peri* C−H bond of 1-naphthols by Rh and Ru catalysts.[9] Despite extensive research, the oxidative C−H/N−H annulation of 1-naphthylanilides with alkynes via *peri* C−H bond cleavage was rarely reported. Only one example of Rh-catalyzed intramolecular annulation of an alkyne-tethered naphthylamide has been reported to proceed through *peri* C−H bond cleavage due to the geometrically favorable rhodacycle intermediate.[4] It was also reported that the reaction of *N*-(1-naphthyl)sulfonamides with alkynes in the presence of an Ir catalyst took place via *peri* C−H bond cleavage to give the *peri*-vinylation products instead of the annulation products.[10] It would be highly desirable to control the selective cleavage of *peri* C−H and *ortho* C−H bonds of the same aromatic substrates by simply tuning catalyst systems, which may construct various fused π-conjugated polyheterocycles chemoselectively.

Initially, we studied various conditions with the $[Cp^*RhCl_2]_2$ catalyst at 110 °C for oxidative annulation of ethyl naphthalen-1-ylcarbamate (**1a**) with diphenylacetylene (**2a**) to obtain the *N*-protected 2,3-diphenyl-1*H*-benzo[*de*]quinoline (**3a**) and 2,3-diphenyl-1*H*-benzo[*g*]indole (**4a**) chemoselectively (Table 1). In the presence of the $Cu(OAc)_2{\cdot}H_2O$ oxidant without using additives, the use of polar solvents such as *tert*-amyl alcohol (*t*-AmOH) and *N*,*N*-dimethylformamide (DMF) gave much higher yields of the benzoquinoline product **3a** than that of nonpolar solvents such as dichloroethane (DCE) and toluene (entries 1−4). Surprisingly, the product **3a** was observed as a sole product without formation of the benzoindole product **4a**. It is noted that $[RuCl_2(p\text{-cymene})]_2$ and $Pd(OAc)_2$ catalysts, which had been used successfully in the oxidative annulation of acetanilides and benzamides,[5,7] combined with $Cu(OAc)_2{\cdot}H_2O$ oxidant in DMF were almost ineffective, affording **3a** in <5% yields.[11] Other oxidants AgOAc and Ag_2CO_3 were also active to give **3a** in complete chemoselectivity with the latter favored for the formation of **3a** in a higher yield of 96% (entries 5 and 6).

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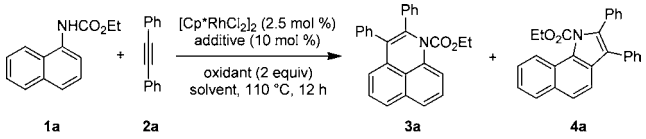
Table 1. Optimization of Reaction Conditions for Chemoselective Formation of 3a and 4a[a]



1a 2a 3a 4a

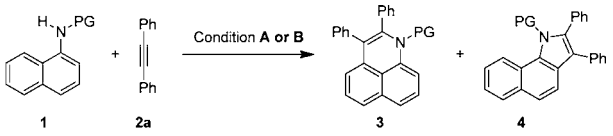
entry	additive	oxidant	solvent	3a (%)[b]	4a (%)[b]
1	none	$Cu(OAc)_2·H_2O$	DCE	13	0
2	none	$Cu(OAc)_2·H_2O$	toluene	14	0
3	none	$Cu(OAc)_2·H_2O$	*t*-AmOH	72	0
4	none	$Cu(OAc)_2·H_2O$	DMF	88	0
5	none	AgOAc	DMF	73	0
6	none	Ag_2CO_3	DMF	96	0
7[d]	none	Ag_2CO_3	DMF	98[c]	0
8	$AgSbF_6$	$Cu(OAc)_2·H_2O$	DMF	64	2
9	$AgSbF_6$	$Cu(OAc)_2·H_2O$	DCE	0	98
10	$AgSbF_6$	AgOAc	DCE	0	96
11	$AgSbF_6$	Ag_2CO_3	DCE	30	11
12	AgOTf	$Cu(OAc)_2·H_2O$	DCE	0	64
13	$AgBF_4$	$Cu(OAc)_2·H_2O$	DCE	0	74
14[e]	$AgSbF_6$	$Cu(OAc)_2·H_2O$	DCE	0	98[c]

[a]Reaction conditions: **1a** (0.25 mmol), **2a** (0.5 mmol), $[Cp^*RhCl_2]_2$ (2.5 mol %), additive (10 mol %), oxidant (2 equiv), solvent (2 mL), Ar atmosphere, 110 °C, 12 h. [b]^{1}H NMR yield was determined using CH_2Br_2 as an internal standard. [c]Isolated yields. [d]Reaction temperature is 70 °C. [e]**2a** (1.2 equiv), $[Cp^*RhCl_2]_2$ (1.5 mol %), $AgSbF_6$ (6 mol %), and $Cu(OAc)_2·H_2O$ (50 mol %) were used under an O_2 (1 atm) atmosphere at 100 °C.

Further investigations revealed that **3a** could be obtained in 98% yield at a decreased temperature of 70 °C (entry 7). The cationic catalyst $[Cp^*RhCl_2]_2/AgSbF_6$ which had been utilized in acetanilides annulations[3a] exhibited lower efficiency and selectivity in the presence of $Cu(OAc)_2·H_2O$ oxidant in DMF at 110 °C, affording **3a** in 64% yield together with a 2% yield of **4a** (entry 8). However, we were pleased to find that, after switching solvent to DCE in this cationic catalyst system, the chemoselectivity of the product was changed drastically, giving the benzoindole product **4a** as a sole product in 98% yield (entry 9). The other oxidant AgOAc was also active to give **4a** selectively (entry 10), but the Ag_2CO_3 oxidant, which has been successfully used in the formation of **3a**, produced a mixture of **3a** and **4a** with low efficiency and selectivity (entry 11). The AgOTf and $AgBF_4$ instead of $AgSbF_6$ as a cationic source were also active to give **3a** selectively with relatively lower yields of 64% and 74% yields, respectively (entries 12 and 13). Further investigations showed that reduction of $[Cp^*RhCl_2]_2/AgSbF_6$ loading to 1.5/6 mol % and $Cu(OAc)_2·H_2O$ oxidant to 0.5 equiv gave a 98% yield of **4a** with exclusive chemoselectivity under an O_2 (1 atm) atmosphere at 100 °C (entry 14). It was also found that the use of $[Cp^*Rh(CH_3CN)_3][SbF_6]_2$[3b] as a catalyst instead of $[Cp^*RhCl_2]_2$ and $AgSbF_6$ gave a high yield of **4a** with exclusive selectivity,[11] supporting the important role of the cationic Rh(III) complex for the selective *ortho* C−H activation. These results clearly indicate that the neutral Rh(III) catalyst in DMF favors the formation of the benzoquinoline product, while the use of a cationic Rh(III) catalyst in DCE leads to benzoindole products exclusively.

Various *N*-protecting groups of 1-naphthanilide (**1**) were investigated under our optimal conditions obtained from Table 1, entries 7 (condition A) and 14 (condition B). As shown in Table 2, the use of benzyl- (**1aa**) and tosyl-protected (**1ab**) 1-

Table 2. Effect of *N*-Protecting Groups of 1-Naphthylanilides



1 2a 3 4

Condition **A**: $[Cp^*RhCl_2]_2$ (2.5 mol %), Ag_2CO_3 (2 equiv), DMF, 70 °C, 12 h.

Condition **B**: $[Cp^*RhCl_2]_2$ (1.5 mol %), $AgSbF_6$ (6 mol %), $Cu(OAc)_2·H_2O$ (0.5 equiv) DCE, 100 °C, 12 h, O_2 (1 atm).

entry	PG (**1**)	condition	**3** (%)[a]	**4** (%)[a]	**1** (%)[a]
1	Bn (**1aa**)	A	0	0	99
2	Bn (**1aa**)	B	0	0	99
3	Ts (**1ab**)	A	0	0	30
4	Ts (**1ab**)	B	0	0	79
5	Ac (**1ac**)	A	16 (**3ac**)	0	78
6[b]	Ac (**1ac**)	B	0	65 (**4ac**)	10
7	CO_2Me (**1ad**)	A	98 (**3ad**)	0	0
8	CO_2Me (**1ad**)	B	0	98 (**4ad**)	0
9	Boc (**1ae**)	A	72 (**3ae**)	0	23
10	Boc (**1ae**)	B	0	26 (**4ae**)	69
11	pyridyl (**1af**)	A	0	0	0[c]
12	pyridyl (**1af**)	B	0	0	0[c]

[a]Isolated yield. [b]Deprotected product 2,3-diphenyl-1*H*-benzo[*g*]-indole (**4ac′**) was also obtained in 19% yield. [c]Decomposition of **1af** was observed.

naphthylanilides failed to give any products under both conditions A and B (entries 1−4). Under the neutral condition A, the acetyl-protected 1-naphthylanilide **1ac** showed a low conversion to produce the corresponding benzoquinoline product **3ac** in 16% yield, while, under the acidic condition B, the corresponding acetyl-protected benzoindole product **4ac** was obtained in 65% yield together with a small amount of deacetylated benzoindole product **4ac′** (entries 5 and 6). The methyl naphthalen-1-ylcarbamate (**1ad**) gave similar reactivity and selectivity as the ethyl 1-naphthylcarbamate **1a** under conditions A and B (entries 7 and 8). Boc-protected 1-naphthylanilide **1ae** was less active under conditions A and B, affording the corresponding **3ae** and **4ae** in 72% and 26% yields, respectively (entries 9 and 10). The reactions with *N*-(naphthalen-1-yl)pyridin-2-amine (**1af**) resulted in the decomposition without forming any desired products under both conditions A and B (entries 11 and 12). We concluded that the reactivity of the current annulation is mainly dominated by *N*-protecting groups on 1-naphthylanilides, while the chemoselectivity of the products is mainly directed by catalyst systems.

A variety of arylcarbamates (**1**) having *peri* C−H and *ortho* C−H bonds were investigated with internal alkynes (**2**) under condition A to show the perfect selectivity of *peri* C−H activation for the formation of benzoquinoline derivatives as shown in Scheme 1. Ethyl naphthalen-1-ylcarbamates bearing either electron-withdrawing or -donating groups on the naphthyl ring reacted with diphenylacetylene **2a** to produce the corresponding benzoquinoline derivatives **3b**−**3e** in excellent yields as single products. It was found that the substituents, such as Br, NO_2, Me, and MeO, were well tolerated and the reaction for the formation of **3e** with a methoxy-substituent required a higher reaction temperature. This condition was also applicable to the annulation of ethyl quinolin-5-ylcarbamate, producing the benzo[*ij*][2,7]naphthyridine product **3f** in good yield under the prolonged reaction time (48 h). The reaction with larger aromatic substrates, such as fluoranthen-3-ylcarbamate, pyren-1-ylcarbamate, and anthracen-1-ylcarbamate, proceeded unevent-

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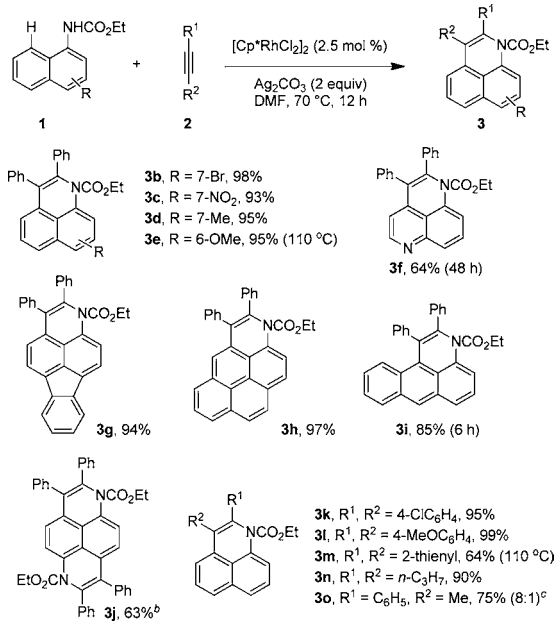
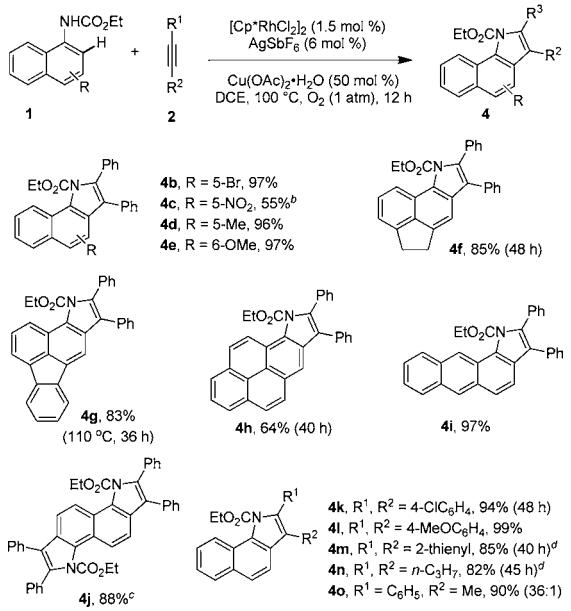
Scheme 1. Rh(III)-Catalyzed Synthesis of Benzoquinoline Derivatives through *peri* C−H Functionalization[a]



[a]Reaction conditions: **1** (0.25 mmol), **2** (0.5 mmol), $[Cp^*RhCl_2]_2$ (2.5 mol %), Ag_2CO_3 (2 equiv), DMF, Ar atmosphere, 70 °C, 12 h. Isolated yields are shown. Unless otherwise noted, only quinoline derivatives **3** were obtained. [b] Reaction conditions: **2a** (4 equiv), $[Cp^*RhCl_2]_2$ (5 mol %), Ag_2CO_3 (4 equiv), 90 °C, 1 h. [c] The reaction was carried out at 50 °C for 24 h.

Scheme 2. Rh(III)-Catalyzed Synthesis of Benzoindole Derivatives through *ortho* C−H Functionalization[a]



[a]Reaction conditions: **1** (0.25 mmol), **2** (0.3 mmol), $[Cp^*RhCl_2]_2$ (1.5 mol %), $AgSbF_6$ (6 mol %), $Cu(OAc)_2{\cdot}H_2O$ (50 mol %), DCE, O_2 (1 atm), 100 °C, 12 h. Isolated yields are shown. Unless otherwise noted, only benzoindole derivatives **4** were obtained. [b] $[Cp^*RhCl_2]_2/AgSbF_6$ (2.5/10 mol %) was used for 48 h, and **3c** was observed in 2% yield. [b] Reaction conditions: **2a** (2.4 equiv), $[Cp^*RhCl_2]_2/AgSbF_6$ (3/12 mol %), $Cu(OAc)_2{\cdot}H_2O$ (1 equiv), O_2 (1 atm). [d] $[Cp^*RhCl_2]_2/AgSbF_6$ (2.5/10 mol %) were used at 110 °C.

fully to give the resulting π-conjugated polyheterocycles **3g−3i** with high conjugation extension in high yields. It is worth noting that diethyl naphthalene-1,5-diyldicarbamate underwent the double annulation to afford the corresponding 1,6-dihydrobenzo[*lmn*][2,7]phenanthroline product **3j** in 63% yield after 1 h. The annulation of **1a** with symmetric diaryl- and dialkylalkynes furnished the corresponding benzoquinoline derivatives **3k−3n** in good to high yields. The reaction of **1a** with an unsymmetric alkyne, 1-phenyl-1-propyne, afforded an 8:1 mixture of regioisomers with **3o** as a predominant product.

Next, the oxidative annulations of various arylcarbamates (**1**) with internal alkynes (**2**) were investigated under the acidic condition B for construction of benzoindole derivatives through *ortho* C−H functionalization as shown in Scheme 2. The annulations of substrates **1** bearing Br, Me, and MeO substituents on the naphthyl ring proceeded through exclusive *ortho* C−H bond cleavage, producing the benzoindole products **4b**, **4d**, and **4e** in excellent yields. It was noted that the reaction of the ethyl naphthalen-1-ylcarbamate possessing a strong electron-withdrawing group such as NO_2 on the naphthyl group furnished the corresponding product **4c** in moderate yield along with a 2% yield of **3c**. The reaction of polycyclic arylcarbamates with **2a** proceeded smoothly to produce the resulting polyheterocycles **4f−4i** in good to high yields with exclusive selectivity, while the formation of **4f−4h** required prolonged reaction times or elevated temperatures. The double annulations of diethyl naphthalene-1,5-diyldicarbamate with **2a** took place efficiently to afford the corresponding 3,8-dihydroindolo[7,6-*g*]indole product **4j** in 88% yield as a sole isomer. Similarly, the reactions of **1a** with symmetric diaryl- and dialkylalkynes produced the desired products **4k−4n** in high yields with exclusive chemoselectivity. In comparison with the formation of **3o**, a much higher regioisomeric ratio of 36:1 was obtained in the reaction of **1a** with an unsymmetric alkyne, such as 1-phenyl-1-propyne, under condition B, in which **4o** was formed as a major product. It was noted that the reaction of **1a** with ethyl acrylate instead of alkynes under condition B produced the corresponding *ortho* C−H olefination product **5a** in 46% yield, while the reaction did not proceed under condition A (Scheme S1, Supporting Information (SI)). The reaction of **1a** with *N*-bromosuccinimide under conditions A and B did not produce any brominated products (Scheme S2, SI).

Based on our experimental outcomes[11] and reported works,[3] the plausible mechanism for the selective formation of **3a** is shown in Scheme 3. The neutral Rh(III) complex coordinates preferentially to the N-atom of carbamate **1a** to form a Rh(III)-amine complex,[12] followed by cyclorhodation at the *peri* C−H bond to afford a five-membered azarhodacycle **A**. Subsequent coordination of alkyne **2a** produces the intermediate **B**, which undergoes a triple bond insertion to give a seven-membered azarhodacycle **C**. It was proposed that, in the case of the unsymmetric alkyne **2o**, the major product **3o** (Scheme 1) should be dominated by the steric effect between the bulky Cp* ligand on rhodium and the sterically more bulky methyl group in the intermediate **C**.[3b] Reductive elimination affords the corresponding benzoquinoline product **3a** along with a Rh(I) complex which is oxidized by Ag_2CO_3 to regenerate the active Rh(III) complex. On the other hand, the cationic Rh(III) complex coordinates to the Lewis basic carbamate oxygen prior to nitrogen presumably due to the Lewis acidity of the Rh(III) catalyst,[3b] followed by cyclorhodation at the *ortho* C−H bond, migratory insertion of alkyne, and reductive elimination to give the benzoindole product **4a**. The use of noncoordinative 1,2-

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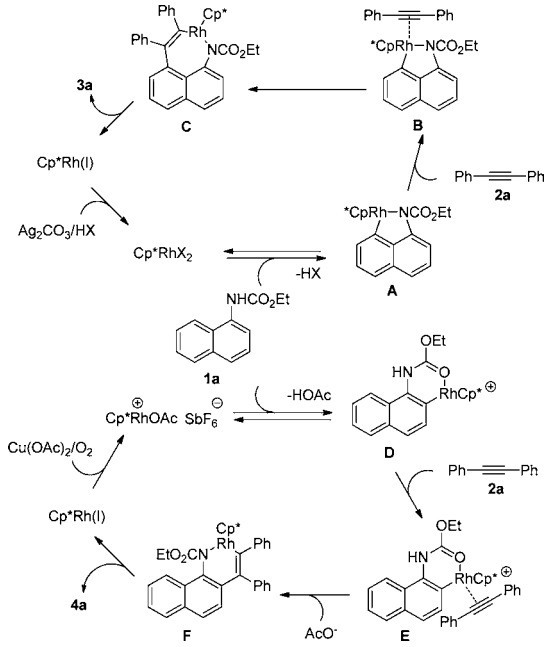
Scheme 3. Proposed Reaction Mechanism



dichloroethane solvent with the cationic Rh(III) catalyst may exhibit a higher Lewis acidity of the Rh catalyst compared with the use of coordinative DMF solvent, which favors the coordination of the Rh complex to the carbamate oxygen.

In conclusion, we have demonstrated for the first time that the diverse C−H bonds of naphthylcarbamates could be functionalized regioselectively in the oxidative annulation with alkynes under different Rh catalyst systems. The neutral Rh(III)-catalyst system is favorable for the activation of the *peri* C−H bond of arylcarbamates, and the cationic Rh(III)-catalyst system is crucial for the activation of the *ortho* C−H bond, which lead to the corresponding benzoquinoline and benzoindole derivatives in good to high yields with exclusive chemoselectivity. The present selective annulation reactions provide a useful, practical synthetic method for the construction of versatile, fused polyheterocycles with high π-conjugation extension.

■ ASSOCIATED CONTENT

Supporting Information

Experimental procedures and characterization data. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) For selected reviews on metal-catalyzed aromatic C−H/annulation, see: (a) Tanaka, K., Ed. *Transition-Metal-Mediated Aromatic Ring Construction*; Wiley: New York, 2013. (b) Jin, T.; Zhao, J.; Asao, N.; Yamamoto, Y. *Chem.—Eur. J.* **2014**, *20*, 3554. (c) Zhang, X.-S.; Chen, K.; Shi, Z.-J. *Chem. Sci.* **2014**, *5*, 2146. (d) Yamaguchi, J.; Yamaguchi, A. D.; Itami, K. *Angew. Chem., Int. Ed.* **2012**, *51*, 8960. (e) Arockiam, P. B.; Bruneau, C.; Dixneuf, P. H. *Chem. Rev.* **2012**, *112*, 5879. (f) Wencel-Delord, J.; Droge, T.; Liu, F.; Glorius, F. *Chem. Soc. Rev.* **2011**, *40*, 4740. (g) Ackermann, L. *Chem. Rev.* **2011**, *111*, 1315.

(2) For selected reviews on oxidative annulation, see: (a) Satoh, T.; Miura, M. *Chem.—Eur. J.* **2010**, *16*, 11212. (b) Song, G.; Wang, F.; Li, X. *Chem. Soc. Rev.* **2012**, *41*, 3651. (c) Patureau, F. W.; Wencel-Delord, J.; Glorius, F. *Aldrichimica Acta* **2012**, *45*, 31. (d) Ackermann, L. *Acc. Chem. Res.* **2014**, *47*, 281.

(3) Selected examples using Rh catalysts, for indole: (a) Stuart, D. R.; Bertrand-Laperle, M.; Burgess, K. M. N.; Fagnou, K. *J. Am. Chem. Soc.* **2008**, *130*, 16474. (b) Stuart, D. R.; Alsabeh, P.; Kuhn, M.; Fagnou, K. *J. Am. Chem. Soc.* **2010**, *132*, 18326. (c) Chen, J.; Song, G.; Pan, C.-L.; Li, X. *Org. Lett.* **2010**, *12*, 5426. (d) Wang, C.; Sun, H.; Fang, Y.; Huang, Y. *Angew. Chem., Int. Ed.* **2013**, *52*, 5795. (e) Hoshino, Y.; Shibata, Y.; Tanaka, K. *Adv. Synth. Catal.* **2014**, *356*, 1577. For isoquinolone: (f) Guimond, N.; Gouliaras, C.; Fagnou, K. *J. Am. Chem. Soc.* **2010**, *132*, 6908. (g) Hyster, T. K.; Rovis, T. *J. Am. Chem. Soc.* **2010**, *132*, 10565. (h) Mochida, S.; Umeda, N.; Hirano, K.; Satoh, T.; Miura, M. *Chem. Lett.* **2010**, *39*, 744. For isoquinoline: (i) Morimoto, K.; Hirano, K.; Satoh, T.; Miura, M. *Org. Lett.* **2010**, *12*, 2068. (j) Wei, X.; Zhao, M.; Du, Z.; Li, X. *Org. Lett.* **2011**, *13*, 4636. For oxidant-free reactions: (k) Zhao, D.; Shi, Z.; Glorius, F. *Angew. Chem., Int. Ed.* **2013**, *52*, 12426. (l) Liu, B.; Song, C.; Sun, C.; Zhou, S.; Zhu, J. *J. Am. Chem. Soc.* **2013**, *135*, 16625. (m) Muralirajan, K.; Cheng, C.-H. *Adv. Synth. Catal.* **2014**, *356*, 1571.

(4) Quiñones, N.; Seoane, A.; García-Fandiño, R.; Mascareñas, J. L.; Gulías, M. *Chem. Sci.* **2013**, *4*, 2874.

(5) Selected examples using Pd catalysts: (a) Shi, Z.; Zhang, C.; Li, S.; Pan, D.; Ding, S.; Cui, Y.; Jiao, N. *Angew. Chem., Int. Ed.* **2009**, *48*, 4572. (b) Chen, J.; Pang, Q.; Sun, Y.; Li, X. *J. Org. Chem.* **2011**, *76*, 3523. (c) Yu, Y.; Huang, L.; Wu, W.; Jiang, H. *Org. Lett.* **2014**, *16*, 2146. (d) Xu, Y.-H.; He, T.; Zhang, Q.-C.; Loh, T.-P. *Chem. Commun.* **2014**, *50*, 2784.

(6) Using a Ni catalyst: (a) Shiota, H.; Ano, Y.; Aihara, Y.; Fukumoto, Y.; Chatani, N. *J. Am. Chem. Soc.* **2011**, *133*, 14952. (b) Song, W.; Ackermann, L. *Chem. Commun.* **2013**, *49*, 6638.

(7) Using a Ru catalyst: (a) Ackermann, L.; Lygin, A. V.; Hofmann, N. *Angew. Chem., Int. Ed.* **2011**, *50*, 6379. (b) Ackermann, L.; Lygin, A. V.; Hofmann, N. *Org. Lett.* **2011**, *13*, 3278. (c) Li, J.; John, M.; Ackermann, L. *Chem.—Eur. J.* **2014**, *20*, 5403.

(8) Mahatthananchai, J.; Dumas, A. M.; Bode, J. W. *Angew. Chem., Int. Ed.* **2012**, *51*, 10954.

(9) (a) Mochida, S.; Shimizu, M.; Hirano, K.; Satoh, T.; Miura, M. *Chem.—Asian J.* **2010**, *5*, 847. (b) Thirunavukkarasu, V. S.; Donati, M.; Ackermann, L. *Org. Lett.* **2012**, *14*, 3416. (c) Dooley, J. D.; Chidipudi, S. R.; Lam, H. W. *J. Am. Chem. Soc.* **2013**, *135*, 10829.

(10) Nishinaka, Y.; Satoh, T.; Miura, M.; Morisaka, H.; Nomura, M.; Matsui, H.; Yamaguchi, C. *Bull. Chem. Soc. Jpn.* **2001**, *74*, 1727.

(11) For the detailed optimization and study of the deuterium isotope effect, see Supporting Information.

(12) (a) Li, X.; Gong, X.; Zhao, M.; Song, G.; Deng, J.; Li, X. *Org. Lett.* **2011**, *13*, 5808. (b) Wang, X.; Li, X.; Xiao, J.; Jiang, Y.; Li, X. *Synlett* **2012**, *23*, 1649.