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Cu(II)-Mediated C(sp^2)−H Hydroxylation

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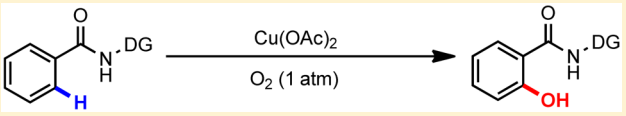
Supporting Information

ABSTRACT: A Cu(II)-mediated *ortho*-C−H hydroxylation using a removable directing group has been developed. The reaction exhibits considerable functional group tolerance. The use of O_2 as an oxidant is crucial for the reactivity. Water is also found to significantly improve this reaction.

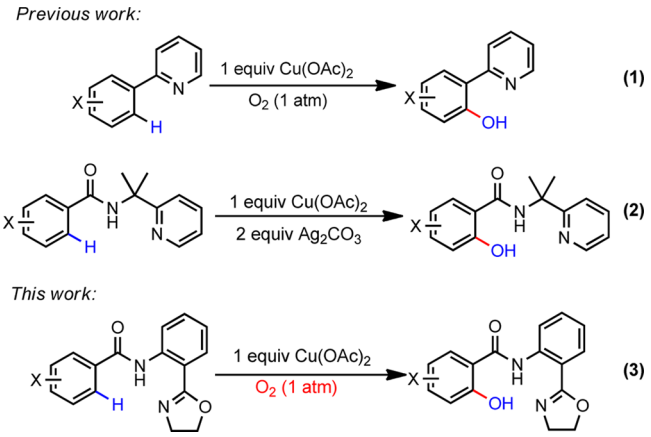


Transition-metal-catalyzed C−H functionalization has recently been recognized as a straightforward and efficient method for the formation of carbon−carbon and carbon−heteroatom bonds.[1] Among them, the direct hydroxylation of C(sp^2)−H bonds[2] has attracted considerable attention from the synthetic community due to the fact that phenols and its derivatives are ubiquitous in organic synthesis, asymmetric catalysis, pharmaceuticals, natural products and molecular materials.[3] In 1990, Fujiwara and co-workers reported a $Pd(OAc)_2$-catalyzed hydroxylation of benzene using molecular oxygen as the sole oxidant. However, this pioneering work retained several limitations such as low efficiency, poor selectivity, and harsh reaction conditions.[4] Subsequently, several groups have explored catalytic direct hydroxylation of arenes using weakly coordinating directing groups.[5,6]

While most reports employed ruthenium[5] and palladium[6] as catalysts, the use of a more economic and inexpensive metal such as copper[7] remained underexplored in C−H hydroxylation reactions. In 2006, our group reported the first $Cu(OAc)_2$ mediated *ortho*-hydroxylation of 2-phenylpyridines using O_2 as the oxidant [Scheme 1, eq 1].[8] Afterward, Cu-mediated functionalization of C−H bonds has achieved great progress.[9−11] Recently, another example of *ortho*-C−H hydroxylation was reported by Shi and co-workers that employed a 2-(pyridine-2-yl)isopropyl (PIP) directing group and used 2 equiv of Ag_2CO_3 as the oxidant [Scheme 1, eq 2].[12] Herein, we describe an efficient and simple method of $Cu(OAc)_2$-mediated *ortho*-selective hydroxylation of arenes employing molecular oxygen as the sole oxidant [Scheme 1, eq 3].

Recently, we reported Cu(II)-mediated *ortho* C−H alkynylation of benzamides with terminal alkynes.[11b] In the course of optimizing reaction conditions, we were surprised to find that the hydroxylated product **2a** was formed under an O_2 atmosphere in 16% yield (Scheme 2). Encouraged by this result, we further investigated this reaction in detail. In the presence of 1 equiv of $Cu(OAc)_2$ and 2 equiv of Na_2CO_3 at 80 °C, the screening of the reaction atmosphere proved that O_2 was the optimal choice, affording the hydroxylated product **2a** in 41% yield (Table 1, entries 1−3). Subsequently, various copper salts were screened and $Cu(OAc)_2$ gave the best yield (see Supporting Information). Furthermore, we found that H_2O plays an important role in this reaction, which was consistent with our previous work,[8] and 20 equiv of H_2O

Scheme 1. Cu-Mediated C−H Hydroxylation



Scheme 2. Reaction Discovery

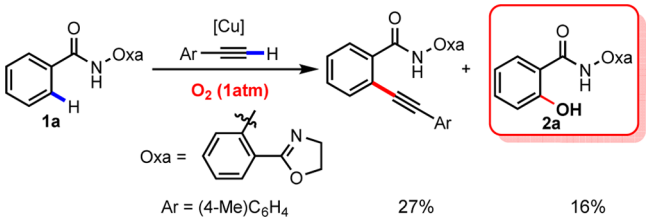


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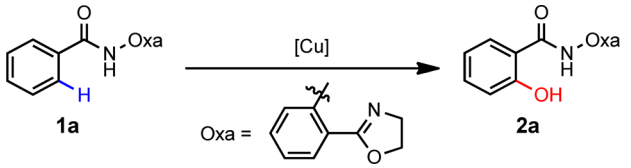
Table 1. Optimization of the Reaction Conditions[a,b]



entry	atmosphere	base	additive (equiv)	yield (%)
1	air	Na_2CO_3	–	31
2	O_2	Na_2CO_3	–	41
3	Ar	Na_2CO_3	–	7
4	O_2	Na_2CO_3	H_2O (5.0)	60
5	O_2	Na_2CO_3	H_2O (10.0)	65
6	O_2	Na_2CO_3	H_2O (20.0)	70
7	O_2	Na_2CO_3	H_2O (30.0)	38
8[c]	O_2	Na_2CO_3	H_2O (20.0)	79
9[c]	O_2	Li_2CO_3	H_2O (20.0)	43
10[c]	O_2	K_2CO_3	H_2O (20.0)	58
11[c]	O_2	Cs_2CO_3	H_2O (20.0)	46
12[c]	O_2	NaOAc	H_2O (20.0)	22
13[c]	O_2	KOAc	H_2O (20.0)	45
14[c,d]	O_2	Na_2CO_3	H_2O (20.0)	79
15[c,d,e]	**O_2**	**Na_2CO_3**	**H_2O (20.0)**	**88**
16[c,d,e,f]	O_2	Na_2CO_3	H_2O (20.0)	15
17[c,d,e,g]	O_2	Na_2CO_3	H_2O (20.0)	43

[a]Reaction conditions: **1a** (0.1 mmol), $Cu(OAc)_2$ (0.1 mmol), base (0.2 mmol), DMSO (1.0 mL), 80 °C, 4 h. [b]Yield determined by ^1H NMR analysis of crude reaction mixture using CH_2Br_2 as an internal standard. [c]6 h. [d]Na_2CO_3 (0.1 mmol). [e]DMSO (2.0 mL). [f]$Cu(OAc)_2$ (0.02 mmol). [g]$Cu(OAc)_2$ (0.05 mmol).

afforded the hydroxylated product **2a** in 70% yield (Table 1, entries 4–7). A small improvement in yield was also obtained by prolonging the reaction time to 6 h (Table 1, entry 8). After a brief screening of bases, Na_2CO_3 remained the optimal choice (Table 1, entries 9–13). Decreasing the amount of Na_2CO_3 to 1.0 equiv also generated the hydroxylated product **2a** in 79% yield (Table 1, entry 14). Furthermore, when the reaction was run at a lower concentration, the yield was further increased to 88% (Table 1, entry 15). Finally, We have also attempted to reduce the amount of copper; when 20 and 50 mol % $Cu(OAc)_2$ were employed under O_2, only 15% and 43% yields were obtained (Table 1, entries 16, 17). Even when others oxidants such as silver salts, peroxide, BQ, and $PhI(OAc)_2$ were employed to replace O_2, the yields were not further improved (see the Supporting Information).

With the optimized reaction conditions in hand, we then examined the scope of benzamide substrates for this reaction. As shown in Scheme 3, both electron-rich and -deficient substituents such as alkyl, methoxy, trifluoromethyl, fluoro, and iodo are well-tolerated under the current reaction conditions, thus generating the corresponding hydroxylated products in moderate to excellent yields. Substrates containing both electron-donating and -withdrawing substituents at the *ortho* position reacted without affecting the yields significantly. For *meta*-substituted substrates, the regioselectivity of the reaction favored formation of less sterically demanding products (**2c**, **2h**, **2o**, **2p**). The iodo substituents are also tolerated (**2k**), although a lower yield was observed, thus providing a useful handle for further synthetic manipulations. Hydroxylation of the vinylated arene produced the desired product in 75% yield (**2m**). As expected, a naphthyl derived substrate also reacted to give the hydroxylated product (**2n**) in 63% yield. Interestingly, bromo and iodo were directly substituted by OH with *o*-bromo or *o*-iodo substrates.

To demonstrate the utility of this hydroxylation reaction, we conducted the reaction on 3 mmol scale, which provided **2a** in 61% yield (see the Supporting Information). Furthermore, the oxazolyamide directing group was smoothly removed by treating product **2a** with KOH/EtOH at 80 °C and the salicylic acid was obtained in 72% yield (Scheme 4).

To probe the mechanism of this reaction, we performed a series of experiments as shown in Scheme 5. First, significant kinetic isotope effects were observed in inter- and intramolecular competition experiments. Next, it was found that addition of the commonly used radical quencher 2,2,6,6-tetramethylpiperidine-*N*-oxyl (TEMPO) has negligible effect on the yield. By combining these results, we can see that the mechanism of this hydroxylation reaction involves a copper-mediated C–H cleavage step rather than an electrophilic aromatic substitution (S_EAr) or a radical pathway. Finally, the *o*-acetoxyl benzamide **5** afforded the hydroxylated product in 71% yield under standard conditions. Based on these results and previous literature,[8,12] we speculate that the reaction might first undergo a $Cu(OAc)_2$-catalyzed acetoxylation followed by a rapid hydrolysis affording the hydroxylated product.

CONCLUSIONS

In summary, we have developed a copper(II)-mediated hydroxylation reaction of aryl C–H bonds using a readily removable directing group. The reaction tolerates a wide range of functional groups, and the use O_2 as the oxidant presents a significant practical advantage.

EXPERIMENTAL SECTION

General Information. All commercial reagents were used without further purification unless specified. ^1H NMR spectra were recorded on a 400 MHz spectrometer, ^{13}C NMR spectra were recorded at 100 and 150 MHz, and ^{19}F NMR spectra were recorded at 375 MHz. The peaks were internally referenced to a TMS (0.00 ppm) or residual undeuterated solvent signal. The following abbreviations were used to explain multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, and br = broad.

Synthesis of Starting Materials. Benzamides **1a–1p**[11a,13] were synthesized as reported in literature.

Preparation of Substrate 5. The 2-(4,5-dihydrooxazol-2-yl)-aniline (0.81 g, 5 mmol) was dissolved with THF (20 mL) in a 50 mL flask, and then Et_3N (0.98 mL, 7.5 mmol) was added to the vigorously stirred solution via a syringe. Then a 2-(chlorocarbonyl)phenyl acetate (5 mmol), which was prepared from the corresponding carboxylic acid and oxalyl chloride, was added dropwise. The reaction mixture was stirred at room temperature for 6 h and quenched with saturated $NaHCO_3$ solution (100 mL). The mixture was extracted with EtOAc (150 mL × 3), washed with saturated NaCl (aq), and dried over Na_2SO_4. Then the solvent was removed in a rotary evaporator to give the crude product which was recrystallized from EtOAc/Hexane to give colorless crystals of the product with the yield 70% (1.13g). Mp 132–133 °C; **^1H NMR** (400 MHz, $CDCl_3$) δ 12.72 (s, 1H), 8.87 (d, J = 8.6 Hz, 1H), 7.89 (d, J = 8.0 Hz, 1H), 7.85 (d, J = 7.6 Hz, 1H), 7.51 (t, J = 7.8 Hz, 2H), 7.35 (t, J = 7.7 Hz, 1H), 7.20 (d, J = 8.1 Hz, 1H), 7.12 (t, J = 7.6 Hz, 1H), 4.38 (t, J = 9.4 Hz, 2H), 4.09 (t, J = 9.4 Hz, 2H), 2.29 (s, 3H); **$^{13}C\{^1H\}$ NMR** (100 MHz, $CDCl_3$) δ 169.3, 164.5, 164.4, 148.6, 139.7, 132.4, 131.7, 129.2, 129.0, 125.9, 123.4, 122.5, 119.8, 113.4, 66.1, 54.4, 21.0; **IR** (film) 1757, 1676, 980, 880, 776, 753 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{18}H_{17}N_2O_4$ $[M + H]^+$ 325.1188, found 325.1196.

General Procedure for Cu(II)-Promoted *ortho*-C–H Hydroxylation of Arenes. To a 25 mL Schlenk-type tube were added

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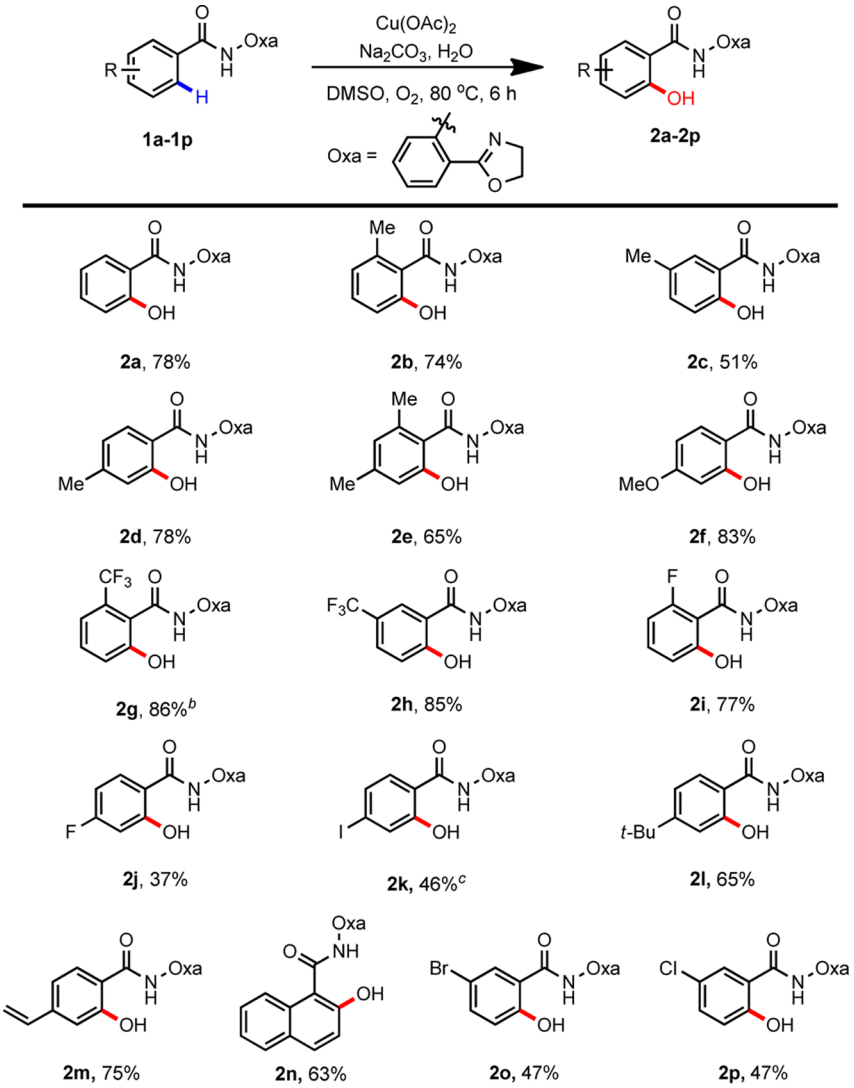
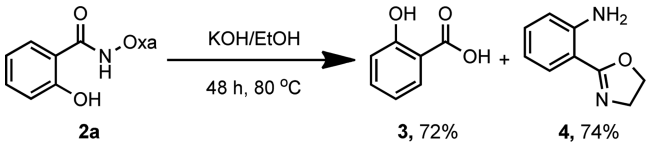
Scheme 3. Scope of Hydroxylation Reaction[a,b,c]



[a]Reaction conditions: **1a−1p** (0.1 mmol), $Cu(OAc)_2$ (0.1 mmol), Na_2CO_3 (0.1 mmol), H_2O (2.0 mmol), DMSO (2.0 mL), 80 °C, O_2, 6 h. [b]DMSO (1.0 mL). [c]60 °C, 3 h.

Scheme 4. Removal of the Oxazolyamide Directing Group



substrates **1a−1p** (0.1 mmol, 1 equiv), H_2O (36 ul, 2.0 mmol), $Cu(OAc)_2$ (18.1 mg, 0.1 mmol), Na_2CO_3 (10.6 mg, 0.1 mmol), and DMSO (2 mL). The reaction tube was evacuated and backfilled with O_2 (6 times). After stirring at 80 °C for 6 h, the reaction mixture was diluted with ethyl acetate and washed with 25% ammonium hydroxide and then brine. The organic fraction was dried over Na_2SO_4 and concentrated in vacuo. The hydroxylated products were purified by silica gel flash column chromatography with a gradient eluent of hexanes and ethyl acetate to give the hydroxylated products.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxybenzamide (**2a**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 40/1); white solid (22 mg, 78%). Mp 124−125 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.23 (s, 1H), 12.45 (s, 1H), 8.81 (d, J = 8.4 Hz, 1H), 7.91 (d, J = 8.0 Hz, 2H), 7.52 (t, J = 7.8 Hz, 1H), 7.42 (t, J = 7.6 Hz, 1H), 7.15 (t, J = 7.6 Hz, 1H), 7.01 (d, J = 8.4 Hz, 1H), 6.93 (t, J = 7.4 Hz, 1H), 4.44 (t, J = 9.4 Hz, 2H), 4.23 (t, J = 9.4 Hz, 2H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 169.7, 164.9, 162.3, 139.2, 134.2, 132.6, 129.4, 126.8, 123.0, 120.2, 118.8, 118.5, 115.5, 114.0, 66.4, 54.5; **IR** (film) 2922, 1635, 1441, 1339, 829, 757 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{16}H_{15}N_2O_3$ $[M + H]^+$ 283.1077, found 283.1082.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxy-6-methylbenzamide (**2b**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 40/1); white solid (22 mg, 74%). Mp 116−117 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 12.64 (s, 1H), 9.90 (s, 1H), 8.75 (d, J = 8.4 Hz, 1H), 7.90 (dd, J = 7.9, 1.4 Hz, 1H), 7.58−7.48 (m, 1H), 7.23 (t, J = 7.8 Hz, 1H), 7.16 (t, J = 7.6 Hz, 1H), 6.84 (d, J = 8.0 Hz, 1H), 6.77 (d, J = 7.6 Hz, 1H), 4.37 (t, J = 9.6 Hz, 2H), 4.05 (t, J = 9.6 Hz, 2H), 2.63 (s, 3H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 169.2, 164.3, 159.1, 138.8, 136.2, 132.4, 132.1, 129.4, 123.3, 122.8, 120.8, 120.0, 115.1, 114.2, 66.3, 54.5, 21.9; **IR** (film) 2930, 1636, 1535, 1446, 1317, 889, 735 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{17}H_{17}N_2O_3$ $[M + H]^+$ 297.1234, found 297.1233.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxy-5-methylbenzamide (**2c**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 80/1); white solid (15 mg, 51%). Mp 169−170 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.23 (s, 1H), 12.19 (s, 1H), 8.83 (d, J = 8.4 Hz, 1H), 7.92 (d, J = 7.6 Hz, 1H), 7.76 (s, 1H),

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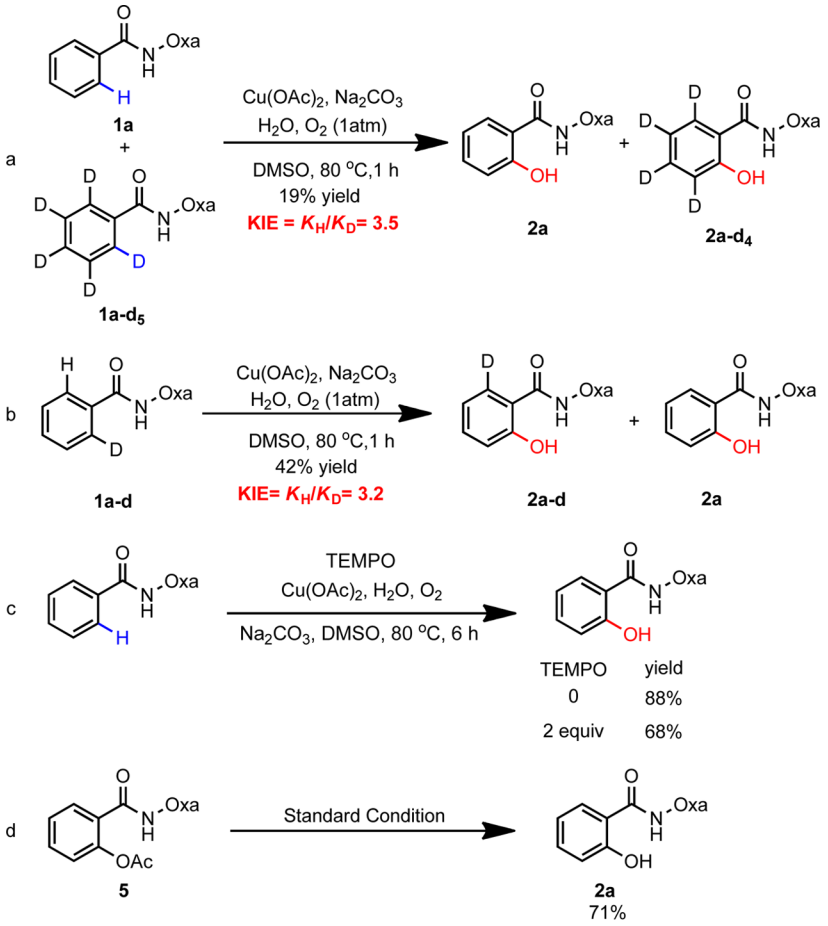
Scheme 5. Investigation of the Mechanism of the C−H Hydroxylation Reaction



7.52 (t, J = 7.6 Hz, 1H), 7.24 (d, J = 8.0 Hz, 1H), 7.15 (t, J = 7.6 Hz, 1H), 6.92 (d, J = 8.4 Hz, 1H), 4.47 (t, J = 9.4 Hz, 2H), 4.26 (t, J = 9.6 Hz, 2H), 2.35 (s, 3H); **^{13}C{^{1}H} NMR** (150 MHz, $CDCl_3$) δ 169.8, 165.0, 160.1, 139.4, 135.1, 132.7, 129.4, 127.7, 127.1, 122.9, 120.1, 118.3, 115.1, 113.9, 66.4, 54.4, 20.8; **IR** (film) 2918, 1621, 1342, 1197, 1087, 810, 758 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{17}H_{17}N_2O_3$ [M + H]$^+$ 297.1234, found 297.1235.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxy-4-methylbenzamide (**2d**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 50/1); white solid (23 mg, 78%). Mp 184−185 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.14 (s, 1H), 12.41 (s, 1H), 8.80 (d, J = 8.4 Hz, 1H), 7.91 (dd, J = 8.0, 1.2 Hz, 1H), 7.79 (d, J = 8.0 Hz, 1H), 7.52 (td, J = 7.6, 0.4 Hz, 1H), 7.13 (td, J = 7.6, 1.6 Hz, 1H), 6.82 (s, 1H), 6.75 (d, J = 8.0 Hz, 1H), 4.45 (t, J = 9.4 Hz, 2H), 4.23 (t, J = 9.4 Hz, 2H), 2.35 (s, 3H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 169.7, 164.9, 162.3, 145.4, 139.3, 132.6, 129.4, 126.7, 122.8, 120.2, 120.1, 118.6, 113.9, 112.9, 66.4, 54.6, 21.7; **IR** (film) 2850, 1614, 1446, 1342, 1220, 833, 756 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{17}H_{17}N_2O_3$ [M + H]$^+$ 297.1234, found 297.1236.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxy-4,6-dimethylbenzamide (**2e**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 40/1); white solid (20 mg, 65%). Mp 129−131 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 12.53 (s, 1H), 10.15 (s, 1H), 8.70 (d, J = 8.4 Hz, 1H), 7.89 (d, J = 7.6 Hz, 1H), 7.52 (t, J = 7.8 Hz, 1H), 7.14 (t, J = 7.6 Hz, 1H), 6.66 (s, 1H), 6.59 (s, 1H), 4.36 (t, J = 9.6 Hz, 2H), 4.04 (t, J = 9.6 Hz, 2H), 2.60 (s, 3H), 2.29 (s, 3H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 169.5, 164.3, 159.6, 142.9, 138.8, 136.1, 132.4, 129.4, 124.0, 123.1, 120.8, 117.0, 115.5, 114.2, 66.3, 54.5, 21.9, 21.4; **IR** (film) 2923, 1638, 1445, 1309, 1056, 828, 744 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{18}H_{19}N_2O_3$ [M + H]$^+$ 311.1390, found 311.1394.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxy-4-methoxybenzamide (**2f**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 40/1); white solid (26 mg, 83%). Mp 143−144 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.04 (s, 1H), 12.78 (s, 1H), 8.78 (d, J = 8.4 Hz, 1H), 7.90 (d, J = 7.6 Hz, 1H), 7.86−7.75 (m, 1H), 7.50 (t, J = 7.6 Hz, 1H), 7.12 (t, J = 7.6 Hz, 1H), 6.50−6.48 (m, 2H), 4.44 (t, J = 9.6 Hz, 2H), 4.23 (t, J = 9.4 Hz, 2H), 3.83 (s, 3H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 169.6, 165.0, 164.6, 164.4, 139.5, 132.6, 129.4, 128.2, 122.6, 120.1, 113.8, 108.5, 107.2, 101.4, 66.3, 55.4, 54.6; **IR** (film) 2970, 1622, 1510, 1343, 1047, 827, 750 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{17}H_{17}N_2O_4$ [M + H]$^+$ 313.1183, found 313.1188.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxy-6(trifluoromethyl)benzamide (**2g**).* Purified by Silica gel plate (hexane/ethyl acetate = 20/1); white solid (30 mg, 86%). Mp 188−189 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 12.51 (brs, 1H), 8.67 (d, J = 8.4 Hz, 1H), 8.40 (brs, 1H), 7.91 (dd, J = 7.8, 1.4 Hz, 1H), 7.53 (td, J = 8.0, 1.6 Hz, 1H), 7.41 (t, J = 8.0 Hz, 1H), 7.28 (d, J = 7.6 Hz, 1H), 7.22−7.16 (m, 2H), 4.34 (t, J = 9.6 Hz, 2H), 3.98 (t, J = 9.5 Hz, 2H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 166.1, 164.0, 156.2, 138.5, 132.4, 131.3, 129.3, 128.0 (q, J_{C-F} = 31.6 Hz), 127.6 (q, J_{C-F} = 8.2 Hz), 123.5 (J_{C-F} = 272.0 Hz), 123.8, 121.1, 121.0, 118.2 (q, J_{C-F} = 5.2 Hz), 114.7, 66.3, 54.4; **IR** (film) 2962, 1639, 1314, 1123, 920, 799, 756 cm^{-1}; **^{19}F NMR** (375 MHz, $CDCl_3$) δ −57.39 (s, 3F); **HRMS** (ESI-TOF) m/z Calcd for $C_{17}H_{14}F_3N_2O_3$ [M + H]$^+$ 351.0951, found 351.0956.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxy-5(trifluoromethyl)benzamide (**2h**).* Purified by Silica gel plate (hexane/ethyl acetate = 20/1); white solid (30 mg, 85%). Mp 167−168 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.64 (s, 1H), 12.82 (s, 1H), 8.79 (d, J = 8.4 Hz, 1H), 8.35 (s, 1H), 7.91 (d, J = 8.0 Hz, 1H), 7.63 (d, J = 8.4 Hz, 1H), 7.52 (t, J = 7.8 Hz, 1H), 7.16 (t, J = 7.6 Hz, 1H), 7.08 (d, J = 8.8 Hz, 1H), 4.46 (t, J = 9.6 Hz, 2H), 4.24 (t, J = 9.4 Hz, 2H); **^{13}C{^{1}H}**

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J. Org. Chem. 2015, 80, 8843−8848

NMR (100 MHz, $CDCl_3$) δ 168.5, 165.1, 164.7, 138.9, 132.8, 130.7 (q, J_{C-F} = 3.3 Hz), 129.4, 124.9 (q, J_{C-F} = 4.1 Hz), 124.1(q, J_{C-F} = 270.1 Hz), 123.4, 121.0 (q, J_{C-F} = 32.9 Hz,), 119.9, 119.2, 115.2, 113.9, 66.6, 54.0; **^{19}F NMR** (375 MHz, $CDCl_3$) δ −61.89 (s, 3F); **IR** (film) 2925, 1659, 1635, 1311, 1080, 903, 805, 770 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{17}H_{14}F_3N_2O_3$ $[M + H]^+$ 351.0951, found 351.0956.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-fluoro-6-hydroxybenzamide (**2i**).* Purified by Silica gel plate (hexane/ethyl acetate = 15/1); white solid (23 mg, 77%). Mp 110−111 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 12.83 (d, J = 8.4 Hz, 1H), 12.71 (s, 1H), 8.67 (d, J = 8.4 Hz, 1H), 7.90 (d, J = 8.0 Hz, 1H), 7.52 (t, J = 7.8 Hz, 1H), 7.34 (dd, J = 14.8, 8.2 Hz, 1H), 7.18 (t, J = 7.6 Hz, 1H), 6.81 (d, J = 8.8 Hz, 1H), 6.65 (dd, J = 11.8, 8.3 Hz, 1H), 4.40 (t, J = 9.6 Hz, 2H), 4.15 (t, J = 9.6 Hz, 2H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 166.8 (d, J_{C-F} = 2.2 Hz), 163.7 (d, J_{C-F} = 1.9 Hz), 163.5 (d, J_{C-F} = 4.4 Hz,), 160.8 (d, J_{C-F} = 251.6 Hz), 138.2, 133.9 (d, J_{C-F} = 12.4 Hz), 132.0, 129.3, 123.7, 122.0, 115.4, 114.2 (d, J_{C-F} = 3.1 Hz), 106.0 (d, J_{C-F} = 24.6 Hz), 105.5 (d, J_{C-F} = 13.7 Hz), 66.4, 54.7; **^{19}F NMR** (375 MHz, $CDCl_3$) δ −109.45 to −109.52 (m, 1F); **IR** (film) 2922, 1605, 1526, 1448, 1275, 1054, 795, 748 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{16}H_{14}FN_2O_3$ $[M + H]^+$ 301.0983, found 301.0985.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-4-fluoro-2-hydroxybenzamide (**2j**).* Purified by Silica gel plate (hexane/ethyl acetate = 10/1); white solid (11 mg, 37%). Mp 156−157 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.20 (s, 1H), 12.78 (s, 1H), 8.77 (d, J = 8.4 Hz, 1H), 7.91 (t, J = 7.8 Hz, 2H), 7.53 (t, J = 7.8 Hz, 1H), 7.16 (t, J = 7.6 Hz, 1H), 6.74−6.59 (m, 2H), 4.46 (t, J = 9.6 Hz, 2H), 4.24 (t, J = 9.4 Hz, 2H); **^{13}C{^{1}H} NMR** (150 MHz, $CDCl_3$) δ 169.1, 166.2 (d, J = 251.7 Hz), 165.1, 164.5 (d, J = 13.7 Hz), 139.1, 132.7, 129.5, 128.8 (d, J = 11.2 Hz), 123.1, 120.3, 114.0, 112.2 (d, J = 2.6 Hz), 106.8 (d, J = 22.7 Hz), 105.1 (d, J = 23.6 Hz), 66.4, 54.5; **^{19}F NMR** (375 MHz, $CDCl_3$) δ −103.74 to −103.81 (m, 1F); **IR** (film) 2911, 1624, 1506, 1346, 1227, 1056, 847, 750 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{16}H_{14}FN_2O_3$ $[M + H]^+$ 301.0983, found 301.0984.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxy-4-iodobenzamide (**2k**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 100/1); white solid (19 mg, 46%). Mp 201−202 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.27 (s, 1H), 12.50 (s, 1H), 8.77 (d, J = 8.8 Hz, 1H), 7.92 (d, J = 7.6 Hz, 1H), 7.59 (d, J = 8.4 Hz, 1H), 7.53 (t, J = 7.8 Hz, 1H), 7.42 (s, 1H), 7.28 (d, J = 8.4 Hz, 1H), 7.16 (t, J = 7.6 Hz, 1H), 4.46 (t, J = 9.4 Hz, 2H), 4.22 (t, J = 9.6 Hz, 2H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 169.3, 165.1, 162.4, 139.0, 132.7, 129.5, 128.1, 127.8, 127.7, 123.2, 120.3, 115.1, 114.0, 100.8, 66.5, 54.5; **IR** (film) 2910, 1622, 1339, 1209, 1053, 839, 803, 752 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{16}H_{14}IN_2O_3$ $[M + H]^+$ 409.0044, found 409.0048.

*4-(tert-Butyl)-N-(2-(4,5-dihydrooxazol-2-yl)phenyl)-2-hydroxybenzamide (**2l**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 80/1); white solid (22 mg, 65%). Mp 149−150 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.16 (s, 1H), 12.40 (s, 1H), 8.82 (d, J = 8.4 Hz, 1H), 7.91 (d, J = 7.6 Hz, 1H), 7.85 (d, J = 8.4 Hz, 1H), 7.51 (t, J = 7.8 Hz, 1H), 7.13 (t, J = 7.4 Hz, 1H), 7.03 (s, 1H), 6.98 (d, J = 8.4 Hz, 1H), 4.44 (t, J = 9.4 Hz, 2H), 4.24 (t, J = 9.4 Hz, 2H), 1.33 (s, 9H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 169.6, 164.9, 162.1, 158.4, 139.4, 132.6, 129.4, 126.5, 122.8, 120.2, 116.5, 115.3, 113.9, 112.8, 66.4, 54.6, 35.0, 30.1; **IR** (film) 2897, 1634, 1581, 1510, 1345, 1158, 828, 750 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{20}H_{23}N_2O_3$ $[M + H]^+$ 339.1703, found 339.1706.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxy-4-vinylbenzamide (**2m**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 80/1); white solid (23 mg, 75%). Mp 150−151 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.20 (s, 1H), 12.45 (s, 1H), 8.80 (d, J = 8.4 Hz, 1H), 7.91 (d, J = 8.0 Hz, 1H), 7.86 (d, J = 8.0 Hz, 1H), 7.52 (t, J = 7.8 Hz, 1H), 7.14 (t, J = 7.6 Hz, 1H), 7.04−6.97 (m, 2H), 6.68 (dd, J = 17.6, 10.8 Hz, 1H), 5.86 (d, J = 17.6 Hz, 1H), 5.38 (d, J = 10.8 Hz, 1H), 4.45 (t, J = 9.4 Hz, 2H), 4.23 (t, J = 9.6 Hz, 2H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 169.4, 165.0, 162.5, 143.3, 139.2, 135.9, 132.6, 129.4, 127.1, 122.9, 120.2, 116.9, 116.7, 115.9, 114.7, 113.9, 66.4, 54.6; **IR** (film) 2919, 1624, 1447, 1344, 1229, 1059, 878, 764 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{18}H_{17}N_2O_3$ $[M + H]^+$ 309.1234, found 309.1235.

*N-(2-(4,5-Dihydrooxazol-2-yl)phenyl)-2-hydroxy-1-naphthamide (**2n**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 80/1); white solid (21 mg, 63%). Mp 162−163 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.31 (s, 1H), 11.16 (s, 1H), 8.93 (d, J = 8.4 Hz, 1H), 8.37 (d, J = 8.4 Hz, 1H), 7.90 (d, J = 7.6 Hz, 1H), 7.85 (d, J = 9.2 Hz, 1H), 7.79 (d, J = 8.0 Hz, 1H), 7.56 (t, J = 8.0 Hz, 1H), 7.44 (t, J = 7.6 Hz, 1H), 7.35 (t, J = 7.2 Hz, 1H), 7.22−7.13 (m, 2H), 4.29 (t, J = 9.6 Hz, 2H), 3.70 (t, J = 9.6 Hz, 2H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 169.2, 164.0, 159.6, 139.2, 134.1, 132.5, 130.4, 129.3, 128.9, 128.7, 126.9, 124.6, 123.4, 123.2, 120.6, 119.2, 114.1, 111.5, 66.3, 54.1; **IR** (film) 2956, 1637, 1534, 1363, 1064, 805, 744 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{20}H_{17}N_2O_3$ $[M + H]^+$ 333.1234, found 333.1236.

*5-Bromo-N-(2-(4,5-dihydrooxazol-2-yl)phenyl)-2-hydroxybenzamide (**2o**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 50/1); white solid (17 mg, 47%). Mp 188−189 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.43 (s, 1H), 12.37 (s, 1H), 8.79 (d, J = 8.4 Hz, 1H), 8.13 (d, J = 2.4 Hz, 1H), 7.92 (dd, J = 8.0, 1.2 Hz, 1H), 7.56−7.48 (m, 2 H), 7.17 (t, J = 7.6 Hz, 1H), 6.91 (d, J = 8.8 Hz, 1H), 4.48 (t, J = 9.2 Hz, 2H), 4.29 (t, J = 9.2 Hz, 2H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 168.4, 165.0, 161.2, 139.0, 136.8, 132.7, 129.9, 129.4, 123.2, 120.4, 120.0, 117.0, 113.9, 110.4, 66.6, 54.2; **IR** (film) 2994, 1625, 1482, 1350, 1213, 944, 761 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{16}H_{14}BrN_2O_3$ $[M + H]^+$ 361.0182, found 361.0184.

*5-Chloro-N-(2-(4,5-dihydrooxazol-2-yl)phenyl)-2-hydroxybenzamide (**2p**).* Purified by flash column chromatography on silica gel (hexane/ethyl acetate = 100/1); white solid (15 mg, 47%). Mp 183−184 °C; **^{1}H NMR** (400 MHz, $CDCl_3$) δ 13.38 (s, 1H), 12.36 (s, 1H), 8.78 (d, J = 8.4 Hz, 1H), 7.95 (d, J = 2.0 Hz, 1H), 7.91 (d, J = 7.6 Hz, 1H), 7.54 (t, J = 7.8 Hz, 1H), 7.35 (dd, J = 8.8, 2.0 Hz, 1H), 7.16 (t, J = 7.6 Hz, 1H), 6.95 (d, J = 8.8 Hz, 1H), 4.46 (t, J = 9.6 Hz, 2H), 4.28 (t, J = 9.4 Hz, 2H); **^{13}C{^{1}H} NMR** (100 MHz, $CDCl_3$) δ 168.5, 165.0, 160.8, 139.0, 134.0, 132.7, 129.4, 126.8, 123.5, 123.2, 120.0, 119.9, 116.4, 113.9, 66.6, 54.2; **IR** (film) 2991, 1626, 1348, 1213, 1056, 935, 769 cm^{-1}; **HRMS** (ESI-TOF) m/z Calcd for $C_{16}H_{14}ClN_2O_3$ $[M + H]^+$ 317.0687, found 317.0688.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b01351.

Experimental procedure and characterization of all new compounds (PDF)

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Notes

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REFERENCES

(1) For selected reviews on C−H functionalization using transition metals, see: (a) Kakiuchi, F.; Sekine, S.; Tanaka, Y.; Kamatani, A.; Sonoda, M.; Chatani, N.; Murai, S. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 62. (b) Chen, X.; Engle, K. M.; Wang, D.-H.; Yu, J.-Q. *Angew. Chem., Int. Ed.* **2009**, *48*, 5094. (c) Giri, R.; Shi, B.-F.; Engle, K. M.; Maugel, N.; Yu, J.-Q. *Chem. Soc. Rev.* **2009**, *38*, 3242. (d) Lyons, T. W.; Sanford, M. S. *Chem. Rev.* **2010**, *110*, 1147. (e) Colby, D. A.; Bergman, R. G.; Ellman, J. A. *Chem. Rev.* **2010**, *110*, 624. (f) Wencel-Delord, J.; Dröge, T.; Liu, F.; Glorius, F. *Chem. Soc. Rev.* **2011**, *40*, 4740. (g) Arockiam, P. B.; Bruneau, C.; Dixneuf, P. H. *Chem. Rev.* **2012**, *112*, 5879. (h) Ackermann, L. *Acc. Chem. Res.* **2014**, *47*, 281.

(2) For selected recent reviews on oxygenation of C−H bond, see: (a) Enthaler, S.; Company, A. *Chem. Soc. Rev.* **2011**, *40*, 4912. (b) Neufeldt, S. R.; Sanford, M. S. *Acc. Chem. Res.* **2012**, *45*, 936. (c) Engle, K. M.; Mei, T.-S.; Wasa, M.; Yu, J.-Q. *Acc. Chem. Res.* **2012**, *45*, 788.

(3) (a) Tyman, J. H. P. *Synthetic and Natural Phenols*; Elsevier: New York, 1996. (b) Rappoport, Z. *The Chemistry of Phenols*; John Wiley & Sons Ltd.: Chichester, U.K., 2003. (c) Huang, W.-Y.; Cai, Y.-Z.; Zhang, Y. *Nutr. Cancer* **2009**, *62*, 1.

(4) Jintoku, T.; Nishimura, K.; Takaki, K.; Fujiwara, Y. *Chem. Lett.* **1990**, 1687.

(5) For ruthenium catalyzed direct hydroxylations of arenes, see: (a) Yang, Y.; Lin, Y.; Rao, Y. *Org. Lett.* **2012**, *14*, 2874. (b) Thirunavukkarasu, V. S.; Hubrich, J.; Ackermann, L. *Org. Lett.* **2012**, *14*, 4210. (c) Thirunavukkarasu, V. S.; Ackermann, L. *Org. Lett.* **2012**, *14*, 6206. (d) Yang, F.; Ackermann, L. *Org. Lett.* **2013**, *15*, 718. (e) Yang, X.; Shan, G.; Rao, Y. *Org. Lett.* **2013**, *15*, 2334. (f) Liu, W.; Ackermann, L. *Org. Lett.* **2013**, *15*, 3484. (g) Yang, F.; Rauch, K.; Kettelhoit, K.; Ackermann, L. *Angew. Chem., Int. Ed.* **2014**, *53*, 11285.

(6) For palladium catalyzed direct hydroxylations of arenes, see: (a) Zhang, Y.-H.; Yu, J.-Q. *J. Am. Chem. Soc.* **2009**, *131*, 14654. (b) Shan, G.; Yang, X.; Ma, L.; Rao, Y. *Angew. Chem., Int. Ed.* **2012**, *51*, 13070. (c) Mo, F.; Trzepkowski, L. J.; Dong, G. *Angew. Chem., Int. Ed.* **2012**, *51*, 13075. (d) Choy, P. Y.; Kwong, F. Y. *Org. Lett.* **2013**, *15*, 270. (e) Yan, Y.; Feng, P.; Zheng, Q.-Z.; Liang, Y.-F.; Lu, J.-F.; Cui, Y.; Jiao, N. *Angew. Chem., Int. Ed.* **2013**, *52*, 5827. (f) Zhang, H.-Y.; Yi, H.-M.; Wang, G.-W.; Yang, B.; Yang, S.-D. *Org. Lett.* **2013**, *15*, 6186.

(7) For reviews of Cu-catalyzed C−H activation, see: (a) Zhang, C.; Tang, C.; Jiao, N. *Chem. Soc. Rev.* **2012**, *41*, 3464. (b) Daugulis, O.; Do, H.-Q.; Shabashov, D. *Acc. Chem. Res.* **2009**, *42*, 1074. (c) Wendlandt, A. E.; Suess, A. M.; Stahl, S. S. *Angew. Chem., Int. Ed.* **2011**, *50*, 11062.

(8) Chen, X.; Hao, X.-S.; Goodhue, C. E.; Yu, J.-Q. *J. Am. Chem. Soc.* **2006**, *128*, 6790.

(9) For recent development of Cu-catalyzed C−H functionalizations, see: (a) Brasche, G.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2008**, *47*, 1932. (b) Ueda, S.; Nagasawa, H. *Angew. Chem., Int. Ed.* **2008**, *47*, 6411. (c) Phipps, R. J.; Grimster, N. P.; Gaunt, M. J. *J. Am. Chem. Soc.* **2008**, *130*, 8172. (d) Mizuhara, T.; Inuki, S.; Oishi, S.; Fujii, N.; Ohno, H. *Chem. Commun.* **2009**, 3413. (e) Monguchi, D.; Fujiwara, T.; Furukawa, H.; Mori, A. *Org. Lett.* **2009**, *11*, 1607. (f) Wang, Q.; Schreiber, S. L. *Org. Lett.* **2009**, *11*, 5178. (g) Huffman, L. M.; Stahl, S. S. *J. Am. Chem. Soc.* **2008**, *130*, 9196. (h) Yang, L.; Lu, Z.; Stahl, S. S. *Chem. Commun.* **2009**, 6460. (i) Klein, J. E. M. N.; Perry, A.; Pugh, D. S.; Taylor, R. J. K. *Org. Lett.* **2010**, *12*, 3446. (j) Shuai, Q.; Deng, G.; Chua, Z.; Bohle, D. S.; Li, C.-J. *Adv. Synth. Catal.* **2010**, *352*, 632. (k) Casitas, A.; King, A. E.; Parella, T.; Costas, M.; Stahl, S. S.; Ribas, X. *Chem. Sci.* **2010**, *1*, 326. (l) Miyasaka, M.; Hirano, K.; Satoh, T.; Kowalczyk, R.; Bolm, C.; Miura, M. *Org. Lett.* **2011**, *13*, 359. (m) Parsons, A. T.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2011**, *50*, 9120. (n) Yang, F.; Xu, Z.; Wang, Z.; Yu, Z.; Wang, R. *Chem. - Eur. J.* **2011**, *17*, 6321. (o) Ni, Z.-K.; Zhang, Q.; Xiong, T.; Zheng, Y.-Y.; Li, Y.; Zhang, H.-W.; Zhang, J.-P.; Liu, Q. *Angew. Chem., Int. Ed.* **2012**, *51*, 1244. (p) Niu, L.; Yang, H.; Yang, D.; Fu, H. *Adv. Synth. Catal.* **2012**, *354*, 2211. (q) Gallardo-Donaire, J.; Martin, R. *J. Am. Chem. Soc.* **2013**, *135*, 9350. (r) Bhadra, S.; Dzik, W. I.; Gooßen, L. J. *Angew. Chem., Int. Ed.* **2013**, *52*, 2959. (s) Huang, P.-C.; Gandeepan, P.; Cheng, C.-H. *Chem. Commun.* **2013**, *49*, 8540. (t) Shen, Y.; Chen, J.; Liu, M.; Ding, J.; Gao, W.; Huang, X.; Wu, H. *Chem. Commun.* **2014**, *50*, 4292.

(10) For Cu-catalyzed C−H functionalizations using amide-amino-quinoline as a directing group, see: (a) Tran, L. D.; Popov, I.; Daugulis, O. *J. Am. Chem. Soc.* **2012**, *134*, 18237. (b) Roane, J.; Daugulis, O. *Org. Lett.* **2013**, *15*, 5842. (c) Tran, L. D.; Roane, J.; Daugulis, O. *Angew. Chem., Int. Ed.* **2013**, *52*, 6043. (d) Truong, T.; Klimovica, K.; Daugulis, O. *J. Am. Chem. Soc.* **2013**, *135*, 9342. (e) Nishino, M.; Hirano, K.; Satoh, T.; Miura, M. *Angew. Chem., Int. Ed.* **2013**, *52*, 4457. (f) Wang, Z.; Ni, J.; Kuninobu, Y.; Kanai, M. *Angew. Chem., Int. Ed.* **2014**, *53*, 3496. (g) Wu, X.; Zhao, Y.; Zhang, G.; Ge, H. *Angew. Chem., Int. Ed.* **2014**, *53*, 3706. (h) Katayev, D.; Pfister, K. F.; Wendling, T.; Gooßen, L. J. *Chem. - Eur. J.* **2014**, *20*, 9902. (i) Dong, J.; Wang, F.; You, J. *Org. Lett.* **2014**, *16*, 2884. (j) Wang, S.; Guo, R.; Wang, G.; Chen, S.-Y.; Yu, X.-Q. *Chem. Commun.* **2014**, *50*, 12718.

(11) For Cu-catalyzed C−H functionalizations using amide-oxazoline as a directing group, see: (a) Shang, M.; Sun, S.-Z.; Dai, H.-X.; Yu, J.-Q. *J. Am. Chem. Soc.* **2014**, *136*, 3354. (b) Shang, M.; Wang, H.-L.; Sun, S.-Z.; Dai, H.-X.; Yu, J.-Q. *J. Am. Chem. Soc.* **2014**, *136*, 11590. (c) Shang, M.; Sun, S.-Z.; Wang, H.-L.; Laforteza, B. N.; Dai, H.-X.; Yu, J.-Q. *Angew. Chem., Int. Ed.* **2014**, *53*, 10439. (d) Shang, M.; Sun, S.-Z.; Dai, H.-X.; Yu, J.-Q. *Org. Lett.* **2014**, *16*, 5666. (e) Wang, H.-L.; Shang, M.; Sun, S.-Z.; Zhou, Z.-L.; Laforteza, B. N.; Dai, H.-X.; Yu, J.-Q. *Org. Lett.* **2015**, *17*, 1228.

(12) Li, X.; Liu, Y.-H.; Gu, W.-J.; Li, B.; Chen, F.-J.; Shi, B.-F. *Org. Lett.* **2014**, *16*, 3904.

(13) Giri, R.; Maugel, N. L.; Foxman, B. M.; Yu, J.-Q. *Organometallics* **2008**, *27*, 1667.

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