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Synthesis of aryl alkynyl carboxylic acids and aryl alkynes from propiolic acid and aryl halides by site selective coupling and decarboxylation

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ABSTRACT

The coupling of propiolic acid with aryl iodides afforded the aryl alkynyl carboxylic acids and aryl alkynes in generally good yields. Aryl alkynyl carboxylic acids were obtained when the reaction was performed in the presence of $Pd(PPh_3)_2Cl_2$ (2.5 mol %), dppb (5.0 mol %) and DBU (5 equiv) at 50 °C. For the synthesis of the terminal aryl alkynes, the reaction was conducted in the presence of $Pd(PPh_3)_2Cl_2$ (2.5 mol %), dppb (5.0 mol %), DBU (5.0 equiv), and $Cu(acac)_2$ (10 mol %) at 25 °C for 5 h, and further reacted at 60 °C for 6 h.

In 1966, Nilsson reported the first decarboxylative Ullmann coupling reaction.[1] However, it was not practical because it gave a low yield, had limited scope and required a large amount of Cu_2O and high temperature. Therefore, it garnered little attention in organic synthesis for 35 years until Myers reported the palladium-catalyzed decarboxylative Heck-type reaction in 2002.[2] Four years later, Gooβen developed a practical and efficient large scale synthesis of biaryls by using decarboxylative coupling.[3] Carboxylic acids have several advantages as surrogates of organometallic nucleophiles. They are stable, easy to make and store, and readily available. In addition, they produce environmentally benign carbon dioxide as a byproduct in the decarboxylative coupling reaction instead of producing metal waste. A variety of decarboxylative coupling reactions of carboxylic acids have been developed over the past few decades.[4] Recently, we first reported the decarboxylative coupling of alkynyl carboxylic acids and aryl halides using a palladium catalyst, which provides an efficient method for the synthesis of unsymmetrical and symmetrical diaryl alkynes.[5] Aryl alkynes are important building blocks in the preparation of pharmaceutical[6] and conjugated functional materials.[7] Classically, the Sonogashira reaction, which is the coupling of aryl halides and terminal alkynes by palladium and copper catalysts in the presence of an amine base, has been widely used for the preparation of aryl alkynes.[8] The employment of alkynyl carboxylic acids as an alternative to terminal alkynes provides a very useful tool in the handling of alkynes with a low boiling point and might prevent the dimerization of the terminal alkynes which are byproducts in the Sonogashira reaction.

Since we first reported the decarboxylative coupling of alkynyl carboxylic acids, a variety of such reactions involving alkynyl carboxylic acids have been reported by many research groups.[9] However, the number of commercially available alkynyl carboxylic acids is limited. There are several methods of preparing alkynyl carboxylic acids (Scheme 1). For example, the carboxylation of a terminal alkyne using a copper[10] or silver[11] catalyst in the presence of a strong base, and the oxidation of aldehydes[12] or alcohols.[13] However, these methods have some drawbacks. In the former case, the requirement of a strong base affords low functional group tolerance. In the latter case, the preparation of the corresponding alcohols and aldehydes needs a multistep process. In the case of aryl alkynyl carboxylic acids, the most popular way is the carbonylation of terminal aryl alkynes synthesized using the Sonogashira coupling reaction of aryl halides and alkynes.[14] However, this requires an expensive protected alkyne source such as trimethylsilylacetylene and 2-methylbut-3-yn-2-ol for the preparation of the terminal aryl alkynes. The direct coupling of aryl halides with propiolates or propiolic acid has been reported. However, it is known to produce low yields in the Sonogashira coupling of terminal alkynes bearing electron withdrawing groups such as esters,[15] although the employment of the diarylidodium salt has been reported to increase the yield of the products.[16] Nonetheless, an additional step is needed to convert the coupled products into carboxylic acids.[17] In the case of the direct coupling reactions with propiolic acid, examples of the successful isolation of the product are rare. To the best of our knowledge, only phenyl iodide led to the successful isolation of its product, phenyl propiolic acid, in

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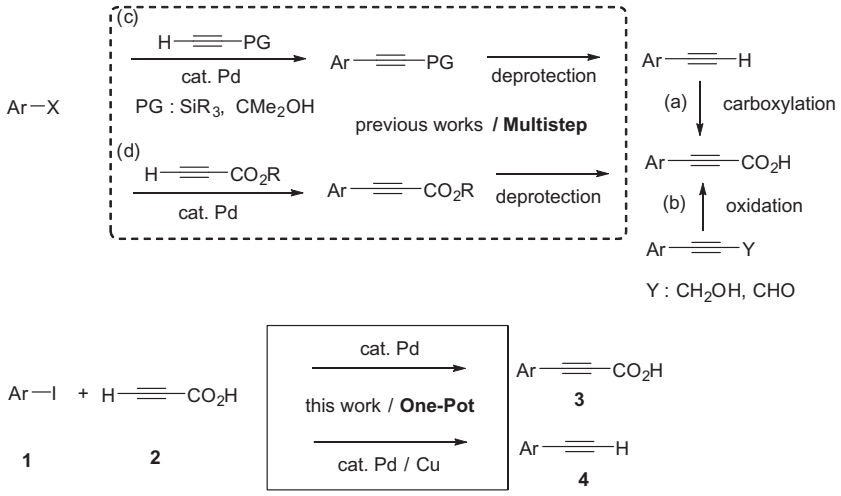


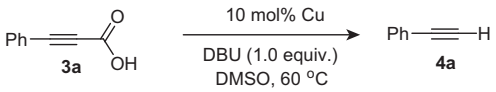
Scheme 1. The synthesis of aryl alkynyl carboxylic acids and aryl alkynes.

the palladium-catalyzed coupling reaction with propiolic acid.[18] Considering the increasing attention being given to the decarboxylative coupling reaction with aryl alkynyl carboxylic acids, a simple and general preparation method is required for the expansion of these coupling reactions. In addition, propiolic acid might be employed as the alkyne source in the generation of terminal aryl alkynes from one-pot sequential reactions consisting of the Sonogashira and decarboxylation reactions. Herein, we report a practical synthesis of aryl alkynyl carboxylic acids and aryl acetylenes from the coupling of propiolic acid and aryl iodides.

For the one-pot synthesis of terminal aryl alkynes from the coupling of propiolic acid and aryl halides, it is necessary for the Sonogashira coupling and decarboxylation reactions to proceed in a stepwise manner. It was found that the Sonogashira coupling of propiolic acid is faster than the decarboxylative coupling reactions, and the selective coupling reaction of aryl iodide and propiolic acid was optimized in our previous report. Therefore, we first investigated the decarboxylation of phenyl propiolic acid. Kolarovič reported that CuCl acted as a catalyst for the decarboxylation of 2-alkynoic acids. Considering the one-pot reaction conditions for the synthesis of phenyl acetylene (**4a**), a variety of copper sources were screened in the presence of DBU, because DBU is used as a base for the preparation of phenyl propiolic acid (**3a**). The results are summarized in Table 1.

When CuCl, which showed good results in the decarboxylation by Kolarovič, was employed, phenyl acetylene was formed in a 43% yield (entry 1). CuBr and CuI produced the decarboxylated product in 24% and 48% yields, respectively (entries 2 and 3). Copper(II) complexes such as $CuCl_2$, $CuBr_2$, and $Cu(OAc)_2$ gave very low yields of the product (entries 4, 5 and 6). Interestingly, when $Cu(acac)_2$ was used as a catalyst, the desired product **4a** was obtained in an 83% yield (entry 7). No homocoupled product, 1,4-diphenylbuta-1,3-diyne, was found.[19] As Kolarovič reported, we also found that the decaroboxylative reaction occurred in the absence of DBU or copper,[20] however, both cases afforded lower yields than that in the presence of both.

Table 1
Screening of copper sources for decarboxylation[a]



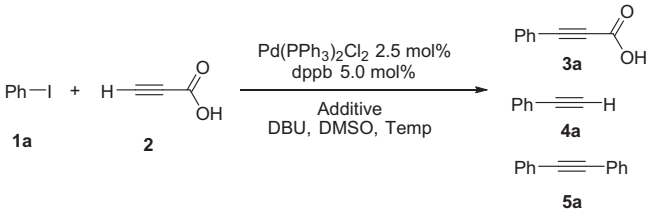
Entry	Cu	Yield[b] (%)
1	CuCl	43
2	CuBr	24
3	CuI	48
4	$CuCl_2$	3
5	$CuBr_2$	4
6	$Cu(OAc)_2$	17
7	$Cu(acac)_2$	83

[a] Reaction Conditions: **3a** (1.0 mmol), Cu (0.1 mmol), DBU (1.0 mmol), and DMSO (3.0 mL) at 60 °C for 6 h.
[b] Yield was determined by GC after the treatment with aqueous NH_4Cl.

With the success of the decarboxylation of phenyl propiolic acid, we next investigated the coupling reaction of phenyl iodide and propiolic acid in the absence or presence of the copper catalyst. The results are summarized in Table 2.

In our previous study, phenyl propiolic acid was converted into methyl phenyl propiolate for the determination of the yield, because it was unstable in the acidic workup process. We found that the treatment with cold 1 N HCl(aq) was an important factor to obtain the desired product without any decomposition in the workup procedure. Based on this technical method, we investigated the effect of the temperature, time, and amount of base on the synthesis of phenyl propiolic acid. When the reaction time reached 5 h, the yield of phenyl propiolic acid was maximized at 87% (entry 2). When the reaction time exceeded 5 h, the yield of phenyl propiolic acid slowly decreased, however the yield of phenyl acetylene did not increase (entry 3). The continuation of the reaction at 80 °C accelerated the decomposition of phenyl propiolic acid without increasing the yield of phenyl acetylene (entry 4). By increasing the amount of DBU to 5 equiv, the yield of phenyl propiolic acid was increased to 92% (entry 6). Coupling at room temperature did not show the complete conversion of phenyl iodide and produced a 63% yield of phenylpropiolic acid (entry 7). Next, the optimized conditions for the decarboxylation of phenyl propiolic acid were combined with the reaction conditions for the coupling reaction of phenyl iodide and propiolic acid. When the reaction was carried out in the presence of $Cu(acac)_2$ at 50 °C, the double coupled product, diphenyl acetylene (**5a**) was formed as the major product. When the reaction temperature was decreased to 25 °C, phenyl propiolic acid was formed in an 85% yield with a trace amount of phenylacetylene (entry 9). In the presence of 10 mol % $Cu(acac)_2$, the reaction at 25 °C for 5 h and additional reaction at 60 °C for 6 h afforded phenyl acetylene in an 80% yield (entry 10), From these results, we made the following conclusions: (1) At 25 °C, the selective coupling of phenyl iodide and propiolic acid occurred to produce phenyl propiolic acid, but it required a long reaction time. However, the reaction rate was accelerated in the presence of $Cu(acac)_2$. (2) At 50 °C, only the Sonogashira coupling

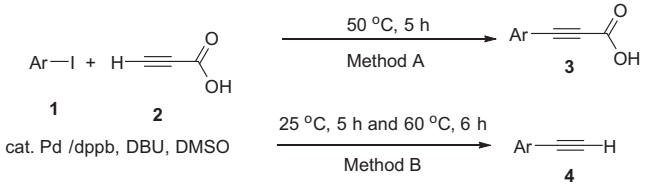
Table 2
The synthesis of phenyl propiolic acid and phenyl acetylene[a]

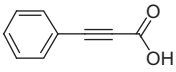
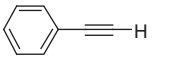
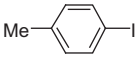
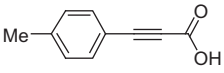
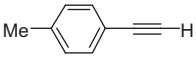
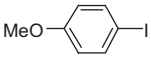
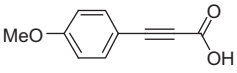
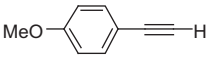
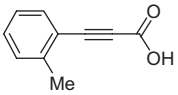
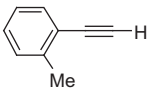
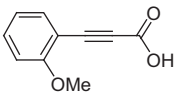


Entry	Additive	Temp (°C)	Time (h)	DBU (equiv)	Conv[b] (%)	Yield[c] (%)		
						3a	**4a**	**5a**
1	—	50	3	2	92	86	6	—
2	—		5	2	95	87	6	—
3	—		12	2	95	62	5	—
4	—	50→80	12→6	2	96	43	4	—
5	—	50	5	3	95	85	2	—
6	—	50	5	5	96	92	2	—
7	—	25	12	5	72	63	2	—
8[c]	$Cu(acac)_2$	50	3	5	90	—	10	40
9[c]	$Cu(acac)_2$	25	5	5	95	85	Trace	—
10[c]	$Cu(acac)_2$	25→60	5→6	5	90	Trace	80	—

[a] Reaction conditions: **1a** (1.0 mmol), **2** (1.0 mmol), $Pd(PPh_3)_2Cl_2$ (0.025 mmol), dppb (0.05 mmol), DBU and DMSO (3.0 mL).
[b] Conversion of **1a** and determined by GC.
[c] 0.1 mmol of $Cu(acac)_2$ was used.

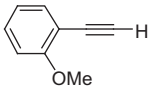
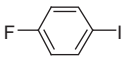
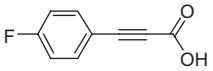
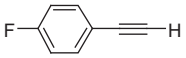
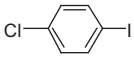
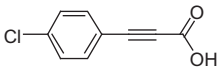
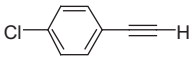
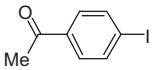
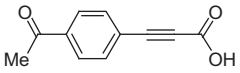
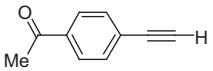
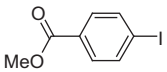
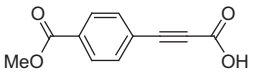
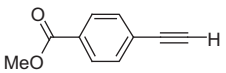
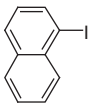
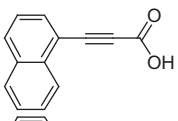
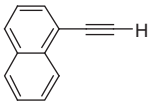
Table 3
The synthesis of alkynyl carboxylic acids and terminal alkynes from aryl iodides[a]



Entry	ArI		Method	Product		Yield[b] (%)
1		**1a**	A		**3a**	92
2			B		**4a**	79
3		**1b**	A		**3b**	72
4			B		**4b**	63
5		**1c**	A		**3c**	67
6			B		**4c**	66
7		**1d**	A		**3d**	56
8			B		**4d**	48
9		**1e**	A		**3e**	48

(*continued on next page*)

Table 3 (*continued*)

Entry	ArI		Method	Product		Yield[b] (%)
10			B		**4e**	42
11		**1f**	A		**3f**	23
12			B		**4f**	15
13		**1g**	A		**3g**	55
14			B		**4g**	21
15		**1h**	A		**3h**	45
16			B		**4h**	30
17		**1i**	A		**3i**	62
18			B		**4i**	42
19		**1j**	A		**3j**	77
20			B		**4j**	71

[a] Reaction conditions: Method **A** : ArI (2.0 mmol), propiolic acid (2.0 mmol), $Pd(PPh_3)_2Cl_2$ (0.05 mmol), dppb (0.1 mmol), and DBU (10.0 mmol) were reacted in DMSO at 50 °C for 5 h; Method **B** : ArI (2.0 mmol), propiolic acid (2.0 mmol), $Pd(PPh_3)_2Cl_2$ (0.05 mmol), dppb (0.1 mmol), $Cu(acac)_2$ (0.2 mmol), and DBU (10.0 mmol) were reacted at 25 °C for 5 h, and further reacted at 60 °C for 6 h.

[b] Isolated yields and characterized by ^1H NMR, ^{13}C NMR see Ref. 21.

occurred in the absence of the copper catalyst, however, both the Sonogashira and decarboxylative couplings occurred to produce diphenyl acetylene in the presence of the copper catalyst. (3) a high temperature (60 °C) was needed for the decarboxylation reaction even in the presence of the copper catalyst.

Using the optimized conditions, we expanded the scope of aryl iodides for the synthesis of aryl alkynyl carboxylic acids and arylalkynes (Table 3). For the aryl alkynyl carboxylic acids, we employed the following conditions: aryl iodide (1.0 equiv), propiolic acid (1.1 equiv), $Pd(PPh_3)_2Cl_2$ (2.5 mol %), dppb (5.0 mol %), DBU (5.0 equiv), and DMSO were reacted at 50 °C for 5 h (Method A). For the synthesis of the terminal aryl alkynes, the reaction was conducted in the presence of $Pd(PPh_3)_2Cl_2$ (2.5 mol %), dppb (5.0 mol %), DBU (5.0 equiv) and $Cu(acac)_2$ (10 mol %) at 25 °C for 5 h, and further reacted at 60 °C for 5 h (Method B). As expected, phenyl iodide afforded phenyl propiolic acid and phenyl acetylene in 92 % and 79 % yields, respectively (entries 1 and 2). Aryl iodides bearing electron donating groups such as methyl and methoxy at the *para* position produced the desired products in good yields, however, *ortho* substituted aryl iodides gave lower yields than the *para* substituted ones due to their steric effects (entries 3–10). Fluoro and chloro substituted aryl iodides afforded the corresponding alkynyl carboxylic acids in 23% and 55% yields (entries 11 and 13), and their terminal alkynes were formed in 15% and 21% yields, respectively (entries 12 and 14). Aryl iodides bearing ketone and ester groups provided the desired products in moderate yields (entries 15–18). We found that the yields from aryl iodides bearing electron withdrawing groups were generally lower than those from aryl iodides bearing electron neutral and donating groups. 1-Iodonaphthalene provided the corresponding alkynyl carboxylic acid in a 77% yield and the terminal alkyne in a 71% yield (entries 19 and 20).

In conclusion, we developed practical and complementary cross-coupling methods for the synthesis of aryl alkynyl carboxylic acids or aryl alkynes from aryl iodides and propiolic acid. In the case of aryl alkynyl carboxylic acids, the site selective coupling reaction of propiolic acid and aryl iodides afforded the desired products, and they were easily isolated with high purity and yields by simple chromatography. In the case of aryl alkynes, the addition of 10 mol % $Cu(acac)_2$ to the palladium-catalyzed reaction mixture and the control of the reaction temperature allowed the desired products to be obtained in high yields. This method does not require an isolation step and does not produce toxic by-products. To the best of our knowledge, there have been no reports on the isolation of aryl alkynyl carboxylic acids from the coupling reaction of aryl iodides and propiolic acid, except for one example involving phenyl iodide. Therefore, this is the first general method for the preparation of both aryl alkynyl carboxylic acids and aryl alkynes from the coupling of aryl iodides and propiolic acid.

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References and notes

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19. When K_2CO_3 was employed as a base instead of DBU, the decarboxylative homocoupled product, 1,4-diphenylbuta-1,3-diyne, was obtained in 21% yield. See: Kim, Y.; Park, A.; Park, K.; Lee, S. *Tetrahedron Lett.* **2011**, *52*, 1766–1769.
20. We found that no decarboxylation of phenyl propiolic acid took place without DBU.
21. *Typical experimental procedure*: **Method A**; $Pd(PPh_3)_2Cl_2$ (35.1 mg, 0.05 mmol), 1,4-bis(diphenylphosphino)butane (42.6 mg, 0.1 mmol), aryl halides (2.0 mmol), and DBU (1.52 g, 10.0 mmol) were combined with DMSO (4.0 mL), in a small round-bottomed flask. Propiolic acid (**1a**) (140.0 mg, 2.0 mmol) was added, and the flask was sealed with a septum. The resulting mixture was placed in an oil bath at 50 °C for 5 h. The reaction was poured into Ethyl acetate and extracted with water saturated by $NaHCO_3$. The aqueous layer was acidified to pH 2.0 by cold 1 N HCl(aq) and extracted with CH_2Cl_2. The organic layer dried over $MgSO_4$, and filtered. The solvent was removed under vacuum, and the resulting crude product was purified by flash chromatography on silica gel to give **3a** (208.6 mg, 96% yield). The spectroscopic data of **3a–j** are as follows.

Compound **3a**: ^{1}H NMR (300 MHz, DMSO d_6) δ 7.64–7.46 (m, 5H); ^{13}C NMR (75 MHz, DMSO-d_6) δ 154.3, 132.6, 130.9, 129.1, 119.0, 84.4, 81.7;

Compound **3b**: ^{1}H NMR (300 MHz, acetone d_6) δ 7.96 (d, J = 7.8 Hz, 2H), 7.73 (d, J = 8.3 Hz, 2H), 2.82 (s, 3H); ^{13}C NMR (75 MHz, acetone d_6) δ 154.6, 142.3, 133.6, 130.4, 117.4, 86.4, 81.4, 21. 6;

Compound **3c**: ^{1}H NMR (300 MHz, acetone d_6) δ 7.48 (d, J = 7.8 Hz, 2H), 6.88 (d, J = 7.8 Hz, 2H), 3.84 (s, 3H); ^{13}C NMR (75 MHz, acetone d_6) δ 161.8, 154.1, 134.7, 114.5, 111.1, 86.0, 80.3, 55.0;

Compound **3d**: ^{1}H NMR (300 MHz, CD_3OD) δ 8.76 (d, J = 7.8 Hz, 1H), 8.60 (t, J = 8.3 Hz, J = 7.5 Hz, 1H), 8.52–8.44 (m, 2H), 3.67 (s, 3H); ^{13}C NMR (75 MHz, CD_3OD) δ 153.1, 140.9, 132.2, 129.8, 128.9, 125.0, 118.3, 83.7, 83.5, 18.7;

Compound **3e**: ^{1}H NMR (300 MHz, acetone d_6) δ 8.80 (d, J = 7.8 Hz, 1H), 8.74 (d, J = 7.8 Hz, 1H), 8.35 (d, J = 7.8 Hz, 1H), 8.26 (t, J = 7.8 Hz, 1H), 5.16 (s, 3H); ^{13}C NMR (75 MHz, acetone d_6) δ 162.4, 154.8, 135.3, 133.4, 121.4, 112.1, 109.3, 85.5, 83.5, 56.2;

Compound **3f**: ^{1}H NMR (300 MHz, acetone d_6) δ 7.50 (d, J = 8.3 Hz, 1H), 7.35 (t, J = 7.8 Hz, 1H), 6.97–6.90 (m, 2H), 3.92 (s, 3H), 3.35 (s, 1H); ^{13}C NMR (75 MHz, acetone d_6) δ 166.4, 163.1, 154.7, 136.3, 117.2, 84.8, 81.8;

Compound **3g**: ^{1}H NMR (300 MHz, acetone d_6) δ 7.66 (d, J = 7.8 Hz, 2H), 7.53 (d, J = 7.8 Hz, 2H); ^{13}C NMR (75 MHz, acetone d_6) δ 154.1, 137.0, 134.9, 129.8, 119.0, 84.1, 82.4;

Compound **3h**: ^{1}H NMR (300 MHz, acetone d_6) δ 8.05 (d, J = 8.3 Hz, 2H), 7.76 (d, J = 7.8 Hz, 2H), 2.62 (s, 3H); ^{13}C NMR (75 MHz, acetone d_6) δ 197.4, 154.4, 139.1, 133.7, 129.3, 124.7, 84.3, 83.9, 26.8;

Compound **3i**: ^{1}H NMR (300 MHz, acetone d_6) δ 8.00 (d, J = 8.3 Hz, 2H), 7.77 (d, J = 7.8 Hz, 2H), 3.87 (s, 3H); ^{13}C NMR (75 MHz, acetone d_6) δ 165.4, 154.0, 132.9, 131.2, 129.5, 123.6, 83.8, 82.9, 52.5;

Compound **3j**: ^{1}H NMR (300 MHz, acetone d_6) δ 8.15 (d, J = 7.8 Hz, 1H), 7.84 (d, J = 8.3 Hz, 1H), 7.76 (d, J = 7.8 Hz, 1H), 7.71 (d, J = 8.3 Hz, 1H), 7.48 (t, J = 7.8 Hz, 1H), 7.40 (t, J = 7.8 Hz, 1H), 7.34 (t, J = 7.8 Hz, 1H); ^{13}C NMR (75 MHz, acetone d_6) δ 154.8, 134.1, 133.8, 133.7, 132.1, 129.4, 128.5, 127.7, 126.0, 125.9, 117.6, 86.5, 84.3.

Method B; $Pd(PPh_3)_2Cl_2$ (35.1 mg, 0.05 mmol), 1,4-bis(diphenylphosphino) butane (42.6 mg, 0.1 mmol), $Cu(acac)_2$ (52.4 mg, 0.2 mmol), aryl halides (2.0 mmol), and DBU (1.52 g, 10.0 mmol) were combined with DMSO (4.0 mL), in a small round-bottomed flask. Propiolic acid (**1a**) (140.0 mg, 2.0 mmol) was dropped at 0–5 °C, and the flask was sealed with a septum. The resulting mixture was stirred at 25 °C for 5 h. Then the reaction temperature was increased to 60 °C, and the mixture was stirred for 6 h. The reaction was poured into Ethyl acetate and washed with water saturated by NH_4Cl. The organic layer dried over $MgSO_4$, and filtered. The solvent was removed under vacuum, and the resulting crude product was purified by flash chromatography on silica gel to give **4a** (230.9 mg, 79% yield). The spectroscopic data of **4a-j** are as follows.

Compound **4a**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.49–7.46 (m, 2H), 7.31–7.27 (m, 3H) 3.05 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) 132.1, 128.7, 128.2, 122.1, 83.6, 77.2;

Compound **4b**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40 (d, J = 7.8 Hz, 2H), 7.13 (d, J = 7.8 Hz, 2H),3.04 (s, 1H), 2.36 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 138.9, 132.0, 129.1, 119.0, 83.8, 76.4, 21.5;

Compound **4c**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.47 (d, J = 7.8 Hz, 2H), 6.87 (d, J = 7.8 Hz, 2H), 3.84 (s, 3H), 3.05 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 159.9, 133.5, 114.1, 113.9, 83.6, 75.7, 55.6;

Compound **4d**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.48 (d, J = 7.9 Hz, 1H), 7.16–7.27 (m, 3H), 3.29 (s, 1H), 2.47 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 140.4, 132.2, 129.4, 128.4, 125.5, 122.5, 80.4, 79.9, 18.6;

Compound **4e**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.50 (d, J = 8.3 Hz, 1H), 7.35 (t, J = 7.8 Hz, 1H), 6.97–6.90 (m, 2H), 3.92 (s, 3H), 3.35 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 160.5, 134.0, 130.2, 120.3, 111.1, 110.5, 81.0, 80.0, 55.7;

Compound **4f**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.40 (d, J = 7.8 Hz, 2H), 7.13 (d, J = 7.8 Hz, 2H), 3.04 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 163.09, 154.0, 138.9 , 115.8, 83.7, 81.4;

Compound **4g**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.41 (d, J = 7.8 Hz, 2H), 7.29 (d, J = 7.8 Hz, 2H), 3.10 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 134.9, 133.3, 128.6, 120.6, 82.5, 78.2;

Compound **4h**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.91 (d, J = 7.8 Hz, 2H), 7.57 (d, J = 7.8 Hz, 2H), 3.26 (s, 1H), 2.61 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 197.2, 136.7, 132.2, 128.1, 126.9, 82.7, 80.3, 26.6;

Compound **4i**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.97 (d, J = 7.8 Hz, 2H), 7.52 (d, J = 7.8 Hz, 2H), 3.89 (s, 3H), 3.23 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.3, 132.0, 130.0, 129.4, 126.6, 82.70, 80.0, 52.2;

Compound **4j**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.15 (d, J = 8.3 Hz, 1H), 8.52 (d, J = 7.8 Hz, 1H), 7.94 (d, J = 7.8 Hz, 1H), 7.67 (d, J = 7.8 Hz, 1H), 7.70 (t, J = 7.8 Hz, 1H), 7.62 (t, J = 7.8 Hz, 1H), 7.51(t, J = 7.8 Hz, 1H) 36.59 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 133.5, 133.0, 131.2, 129.2, 128.2, 126.9, 126.4, 126.0, 125.0, 119.7, 82.0, 81.7.