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Copper-catalyzed tandem intramolecular cyclization/coupling reaction: solvent effect on reaction pathway

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ABSTRACT

In this study, we developed direct methods for the synthesis of 3-substituted indoles from *o*-alkynylanilines by utilizing a copper-catalyzed tandem intramolecular cyclization/coupling reaction under mild and simple reaction conditions. Our investigation revealed that choice of the aprotic polar solvents and additives such as camphorsulfonic acid is critical in this reaction.

Indoles are interesting and valuable because they are widely found in various biologically active natural and artificial compounds.[1] Therefore, the development of efficient methods to synthesize these compounds continues to be an active research area. In particular, the intramolecular cyclization of *o*-alkynylanilines, which are typically prepared from *o*-haloanilines and terminal acetylenes via the Sonogashira reaction, has been widely reported.[2,3] Despite early successes using Pd,[4] Au,[5] or other metals[6] as catalyst, there are limited reports on the direct synthesis of 3-substituted indoles from *o*-alkynylanilines using Cu as catalyst.[7] However, much attention has been paid to Cu catalysis due to the lower cost of copper catalysis.[2a,b]

Recently, we obtained preliminary results in our laboratory when testing the copper-catalyzed cyclization of *o*-alkynylaniline according to Shen's procedure.[7c] Shen and Lu reported that indole **2a** was obtained in 80% yield by the reaction of **1a** in the presence of CuCl (0.5 equiv) in DMSO at 50 °C for 1 h under nitrogen atmosphere (Scheme 1a). We then tested Shen's procedure, and **2a** was obtained in 70% yield as reported; surprisingly, trace amounts of 3-chlorinated product **3a** and homocoupling dimer **4a** were also isolated. Furthermore, when the reaction was conducted under open-air conditions, **2a** was still the major product, similar to the result for the reaction conducted under an inert atmosphere; an increase in the chemical yields of **3a** and **4a** was observed (Scheme 1b). These results imply that the direct introduction of carbon functional groups or halogens to the 3-position of indole is possible under mild reaction conditions. Herein, we describe direct methods for the synthesis of 3-substituted indoles from *o*-alkynylanilines by utilizing a copper-catalyzed tandem intramolecular cyclization/coupling reaction under mild reaction conditions.

In initial studies, we investigated the reaction in various solvents in air because the results of copper catalysis are known to largely depend on the solvent.[7c] The results are shown in Table 1. As a result, nonpolar and polar solvents such as toluene, CH_2Cl_2, EtOAc, THF, acetone, and dioxane were ineffective in promoting the reaction (Table 1, entries 1–6). In contrast, protic polar solvents such as EtOH afforded **2a** in 51% yield as a major product (Table 1, entry 7). Alternatively, further interesting results were obtained when aprotic polar solvents were used. Among them, when using dimethylformamide (DMF) as a solvent, homocoupling product **4a** was obtained as a major product, whereas when using *N*,*N*-dimethyacetamide (DMA) as a solvent, 3-chlorinated indole **3a** was obtained as a major product. These results indicated that this reaction should preferably be conducted in an aprotic polar solvent, and that varying the aprotic polar solvent could affect the reaction pathway.[8]

Recently, Pyne's group reported CuCN-mediated cyclization/cyanation reactions.[7b] However, this method has some drawbacks for practical applications under reaction conditions (typical reaction conditions: in DMF, at 100 °C and under oxygen atmosphere). Thus, we attempted to perform the reaction with copper cyanide under the developed reaction conditions. The results are shown in Table 2. First, the reaction was tested under an air atmosphere and with four aprotic polar solvents, DMA, dimethylsulfoxide (DMSO), *N*-methylpyrrolidone (NMP), and DMF, which showed different tendencies under the reaction conditions shown in Table 1. As expected, the reaction proceeded at room temperature to yield

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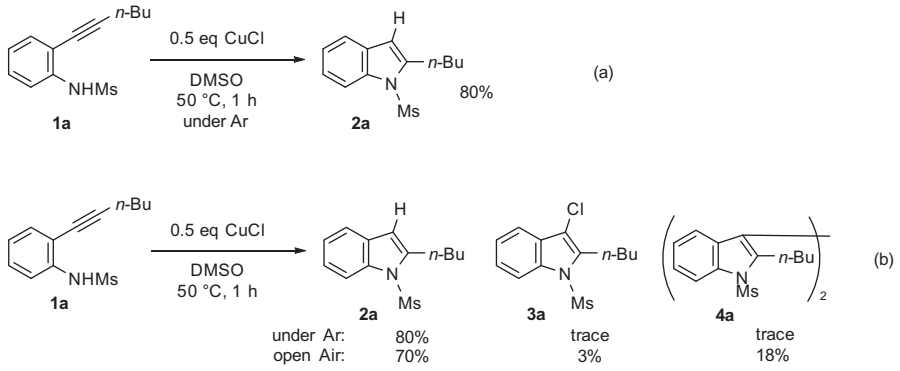
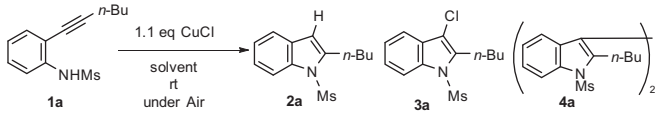


Scheme 1. Synthesis of **2a**, **3a**, and **4a** from **1a**.

Table 1
Reaction of *o*-alkynylanilines (**1a**) with CuCl under air[a]



Entry	Time (h)	Solvent	Yield (%)		
			2a[b]	**3a**[b]	**4a**[c]
1	24	Toluene		No reaction	
2	24	CH_2Cl_2		No reaction	
3	24	EtOAc		No reaction	
4	24	THF		No reaction	
5	24	Acetone		No reaction	
6	24	CH_3CN	Trace	—	—
7	24	EtOH	51	31	6
8	15	DMSO	34	10	34
9	2	DMF	15	15	52
10	4	DMA	8	51	20
11	12	NMP	7	47	30
12	4	NMF[d]	24	24	38
13	3	HMPA	35	25	24

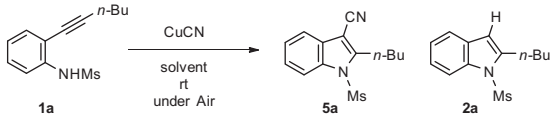
[a] Substrate **1a** (0.2 mmol) and CuCl (0.22 mmol) were stirred in solvent (1.0 mL) at rt under open-air conditions.
[B] Compounds **2a** and **3a** were difficult to separate by silica gel column chromatography. Yield was calculated from NMR spectra of mixture.
[c] Isolated yield.
[d] NMF = *N*-methylformamide.

3-cyanated indole **5a** as a major product with moderate yields (27–56%), and the reaction in DMA yielded better results (Table 2, entries 1–4). Under these reaction conditions, 3-protonated indole **2a** was the major byproduct, and the formation of a homocoupling product was not observed. Next, additive screening was investigated to further improve the yield of **5a**. Unfortunately, the addition of typical ligands for copper catalysts such as proline, triphenylphosphine, inorganic salts, and quaternary ammonium salts was not effective in increasing the yield further (Table 2, entries 5–9). Finally, we discovered that using sulfonic acid such as camphorsulfonic acid (CSA) and *p*-toluene sulfonic acid (TsOH) as an additive was effective in increasing the yield of **5a** (Table 2, entries 10 and 11). In contrast, adding benzoic acid did not have a remarkable effect on the result, implying the additive acidity is the key to improving the yield of **5a** (Table 2, entry 12).

Next, reaction conditions were further optimized in terms of reaction time. The results are shown in Table 3. The reaction time was shortened when the reaction temperature was changed to 40 °C, while the yield of **5a** slightly decreased (Table 3, entry 1). On the other hand, the yield of **5a** significantly decreased when the reaction was performed without CSA due to the increasing formation of **2a**, demonstrating that CSA is essential to obtain a high chemical yield of **5a**. Further improvement of the yield was not observed when the amount of CSA was increased to 0.5 equiv (Table 3, entry 3). Decreasing the amount of copper salt (2.0 or 1.1 equiv) gave a lower yield of **5a** (Table 3, entries 4 and 5). Then, the tuning of the *N*-substituent on aniline was attempted. The reaction of **1b**, bearing the trifluoromethanesulfonyl (Tf) group, yielded only the 3-protonated product **2b** without the formation of **5b** (Table 3, entry 6). When the *N*-protecting group on aniline was changed to trifluoroacetyl (TFA), no reaction was observed at 40 °C; the formation of a new spot was confirmed by thin-layer chromatography at 50 °C, and after 48 h, 5 h (R^1 = H) was isolated in 38% yield along with 41% recovery of **1c** (Table 3, entry 7). Finally, the reaction of a substrate bearing the toluenesulfonyl (Ts) group was completed within 12 h, and **5d** was obtained in 77% yield.

To evaluate the developed methods, other substituents were introduced in the reactions. The results are shown in Table 4. To our delight, substrate **1e**, bearing an aromatic substituent on the acetylene moiety, was found to be applicable to the developed reaction conditions, and the use of DMSO as solvent showed the best results (Table 4, entry

Table 2
Effect of solvent and additives[a]



Entry	Time (h)	Solvent	Additive (equiv)	Yield[b] (%)	
				5a	**2a**
1	72	DMA	—	56	18
2	20	DMSO	—	27	50
3	72	NMP	—	44	32
4	2	DMF	—	30	40
5	72	DMA	PPh_3, 0.2	55	24
6	72	DMA	Proline, 0.2	54	18
7	16	DMA	LiCl, 3	2	91
8	18	DMA	K_2CO_3, 1	5	78
9	17	DMA	Bu_4NBr, 3	0	78
10	96	DMA	CSA, 0.2	81	4
11	96	DMA	TsOH, 0.2	80	2
12	96	DMA	Benzoic acid, 0.2	64	14

[a] Substrate **1a** (0.2 mmol), CuCN (0.6 mmol), and additive were stirred in solvent (1.0 mL) at rt under open-air conditions.
[b] Isolated yield.