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Iron-Mediated Carboarylation/Cyclization of Propargylanilines with Acetals: A Concise Route to Indeno[2,1-*c*]quinolines

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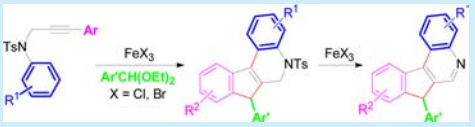
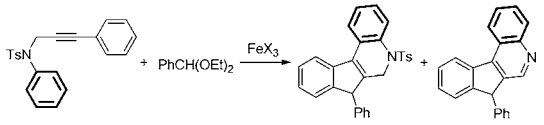
Supporting Information

ABSTRACT: $FeCl_3$- and $FeBr_3$-mediated tandem carboarylation/cyclization of propargylanilines with diethyl benzaldehyde acetals furnished the tetracyclic core of indeno[2,1-*c*]quinolines. 5-Tosyl-6,7-dihydro-5*H*-indeno[2,1-*c*]-quinoline and 7*H*-indeno[2,1-*c*]quinoline derivatives were obtained in good to excellent yields, respectively, by tuning the FeX_3 loadings and/or reaction temperatures.



Construction of functionalized carbo- and heteropolycyclic architectures with minimum operations from relatively simple building blocks has been a challenging task in organic synthesis.[1] Tetracyclic indenoquinoline fused with quinoline[2] and indene[3] frameworks is a common structural unit in a number of biologically active natural products and pharmaceuticals such as DNA topoisomerase inhibitor TAS-103[4] and its analogues **I**[5] and **II**,[6,7] etc., for anticancer treatment. Time-consuming multistep procedures have usually been applied to access an indeno[2,1-*c*]quinoline core consisting of tetracycles A–D, involving Diels–Alder[5] and Friedel–Crafts[6] reactions, cyclization,[8] and addition to carbonyl compounds.[9] Alkynes were documented to undergo versatile cycloaddition, carbocyclization, and/or cycloisomerization[10,11] to form quinolines,[12] indeno[1,2-*b*]quinolines,[13] and indeno[1,2-*c*]quinolines,[14] while indeno[2,1-*c*]quinolines have not yet been prepared by such methods.

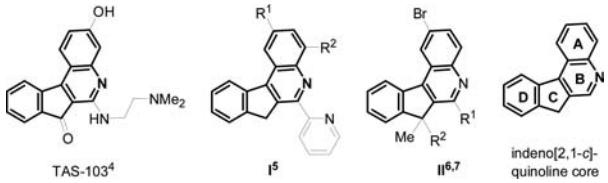
Table 1. Screening of Reaction Conditions[a]



1a 2a 3a 4a

			yield[b] (%)	
entry	[Fe] (equiv)	temp (°C)	**3a**	**4a**
1	$FeCl_3$ (0.2)	80	73	9
2[c]	$FeBr_3$ (0.2)	80	75	14
3	**$FeCl_3$ (0.3)**	**80**	**75**	**18**
4	$FeBr_3$ (0.3)	80	71	19
5	$FeCl_3$ (1.0)	80	56	37
6	$FeBr_3$ (1.0)	80	56	31
7[d]	**$FeCl_3$ (1.0)**	**25**	**72**	**18**
8[d]	$FeBr_3$ (1.0)	25	72	21
9	$FeBr_3$ (2.0)	80		54
10	$FeBr_3$ (2.5)	80		67
11	**$FeBr_3$ (3.0)**	**80**		**82**
12	**$FeCl_3$ (3.0)**	**80**		**73**
13	$FeCl_3 \cdot 6H_2O$ (3.0)	80		43
14	$FeBr_3$ (3.0)	100		69
15	$FeBr_3$ (3.0)	60		69
16	$FeBr_3$ (3.0)	25	34	31
17	$FeCl_3$ (3.0)	25		47

[a]Conditions: **1a** (0.3 mmol), **2a** (0.6 mmol), DCE (3 mL), N_2, 5 h. [b]Isolated yield. [c]95% conversion for **1a**. [d]**2a** (0.45 mmol), CH_2Cl_2 (3 mL), 18 h. DCE = 1,2-dichloroethane.



Recently, iron salts have been paid much attention as promising alternatives to traditional transition-metal catalysts[15] and also employed for the synthesis of polycyclic compounds.[16] $Fe(OTf)_3$ catalyzed the intramolecular hydroarylation of alkynes with electron-deficient arenes, building 1,2-dihydroquinolines and phenanthrenes.[12c] $FeCl_3$ mediated the intramolecular isomerization/cyclodehydration of substituted 2-[(indoline-3-ylidene)(methyl)]benzaldehydes to form benzo[*b*]carbazoles,[16b] which were used for the synthesis of indeno-fused heterocycles.[16c] We recently reported FeX_3-promoted Prins-type cyclization of alkynyl acetals[17] and intermolecular cyclization of diynes with acetals to give tricyclic compounds.[18] Herein, we report FeX_3-mediated carboarylation/cyclization/detosylation of propargylanilines with benzaldehyde acetals for the synthesis of indeno[2,1-*c*]quinolines.

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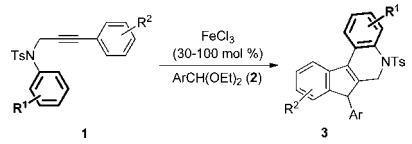
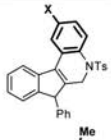
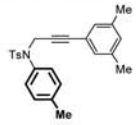
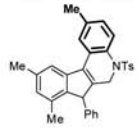
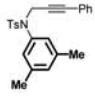
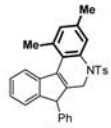
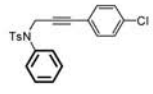
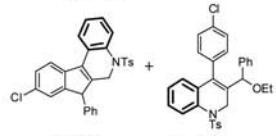
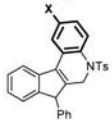
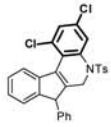
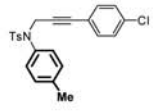
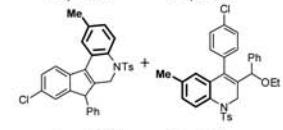
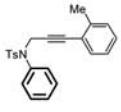
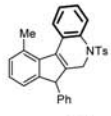
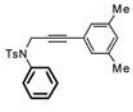
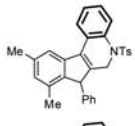
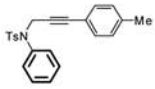
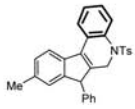
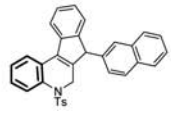
Table 2. $FeCl_3$-Catalyzed Synthesis of 5-Tosyl-6,7-dihydro-5*H*-indeno[2,1-*c*]quinolines (3)[a]



entry	1 / Ar (2)	yield[b]	entry	1 / Ar (2)	yield[b]
1	 **1a**, X = H / Ph (**2a**)	 **3a**, 75%	11	 **1k** / Ph (**2a**)	 **3k**, 89%
2	**1b**, X = Me / Ph (**2a**)	**3b**, 73%			
3	**1c**, X = OEt / Ph (**2a**)	**3c**, 71%			
4	 **1d** / Ph (**2a**)	 **3d**, 82% (90%)[c]	12	 **1l** / Ph (**2a**)	 **3l**, 9% **5a**, 53% **3l**, 42%[d] **5a**, 31%[d]
5	 **1e**, X = Cl / Ph (**2a**)	 **3e**, 82%[d]			
6	**1f**, X = F / Ph (**2a**)	**3f**, 77%[d]			
7	 **1g** / Ph (**2a**)	 **3g**, 78%[d]	13	 **1m** / Ph (**2a**)	 **3m**, 35% **5b**, 46%
8	 **1h** / Ph (**2a**)	 **3h**, 75%[d]			
9	 **1i** / Ph (**2a**)	 **3i**, 77%	14	**1a** / 4-MeC_6H_4 (**2b**)	**3n** (R = 4-Me), 69%[d]
			15	**1a** / 3-MeC_6H_4 (**2c**)	**3o** (R = 3-Me), 71%[d]
			16	**1a** / 4-ClC_6H_4 (**2d**)	**3p** (R = 4-Cl), 73%[d]
			17	**1a** / 4-BrC_6H_4 (**2e**)	**3q** (R = 4-Br), 79%[d]
			18	**1a** / 3-BrC_6H_4 (**2f**)	**3r** (R = 3-Br), 58%
			19	**1a** / 4-FC_6H_4 (**2g**)	**3s** (R = 4-F), 69%
			20	**1a** / 2-FC_6H_4 (**2h**)	**3t** (R = 2-F), 80%
			21	**1a** / 4-$NO_2C_6H_4$ (**2i**)	**3u** (R = 4-NO_2), 63%[d]
			22	**1a** / 3-$CF_3C_6H_4$ (**2j**)	**3v** (R = 3-CF_3), 64%[d]
10	 **1j** / Ph (**2a**)	 **3j**, 64%	23	**1a** / 2-naphthyl (**2k**)	 **3w**, 63%

[a]Conditions: **1** (0.3 mmol), **2** (0.6 mmol), $FeCl_3$ (0.09 mmol), DCE (3 mL), 80 °C, N_2, 5 h. [b]Isolated yield. [c]0.09 mmol $FeBr_3$ was used as the catalyst. [d]Conditions: **1** (0.3 mmol), **2** (0.45 mmol), $FeCl_3$ (0.3 mmol), CH_2Cl_2 (3 mL), 25 °C, N_2, 18 h.

Initially, the reaction of propargylaniline (**1a**) with diethyl benzaldehyde acetal (**2a**) was performed to screen the reaction conditions (Table 1). With 20 mol % $FeCl_3$ as the catalyst at 80 °C, the reaction proceeded to form 5-tosyl-6,7-dihydro-5*H*-indeno[2,1-*c*]quinoline (**3a**, 73%) and 7*H*-indeno[2,1-*c*]-quinoline (**4a**, 9%), achieving 100% conversion for **1a** (Table 1, entry 1). Increasing the FeX_3 loading rendered **1a** to be completely converted (Table 1, entries 1−4), but use of 1 equiv of FeX_3 deteriorated the selectivity to yield **3a** (56%) and **4a** (<40%). Longer reaction time enhanced the yield of **4a** to 42−47%. To our delight, the reaction afforded **3a** in 72% yield at ambient temperature (Table 1, entries 7 and 8). At 80 °C, $FeBr_3$ (3 equiv) acted more efficiently than $FeCl_3$ and $FeCl_3 \cdot 6H_2O$ to generate **4a** (82%) (Table 1, entries 9−13). Varying temperatures at 100 or 60 °C by using $FeBr_3$ as the promoter lowered the yield of **4a** (69%), and ambient temperature led to indiscriminative formation of **3a** (34%) and **4a** (31%) (Table 1, entries 14−17). Thus, the optimal conditions for the preparation of **3a** and **4a** (Table 1, entries 3 and 11) were achieved. It is noted that other Lewis acids such as $SnCl_4$ could also promoted the reaction: under the conditions employed for entry 7 of Table 1, the reaction using 1 equiv of $SnCl_4$ afforded **3a** in 54% yield.

Under the optimized conditions, the substrate scope for the synthesis of **3** was explored (Table 2). Propargylanilines **1a−g** reacted with **2** to afford **3a−g** in 71−90% yields, exhibiting no obvious substituent effect from the NAr moieties (Table 2, entries 1−7). *o*- or *m*-methyl on the aryl group of a propargyl moiety favored the formation of **3h** (75%) and **3i** (77%), while a *p*-methyl lowered the yield of **3j** (64%) (Table 2, entries 8−10). A *p*-methyl on the aryl group of the NAr functional group facilitated the generation of **3k** (Table 2, entry 11). 1,2-Dihydroquinolines **5a** (53%) and **5b** (46%) were isolated from the reactions of **1l** and **1m**, respectively (Table 2, entries 12 and 13). Substituted acetals **2b−k** reacted to give diverse target products **3n−w** (58−80%) (Table 2, entries 14−23). It should be noted that arylpropargylaniline of type **1** bearing a *p*-OMe substituent only reacted to give a product of type **3** in 33% yield. The acetals derived from heterocyclic aromatic aldehydes such as 2-furaldehyde and 2-thiophenaldehyde could not undergo the desired reactions. The acetals of the alkyl aldehydes are not very stable under the stated conditions[17,18] and were not applied in the reactions.

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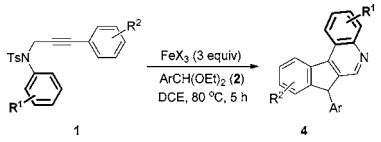
Table 3. FeX_3-Mediated Synthesis of 7*H*-Indeno[2,1-*c*]quinolines (4)[a]

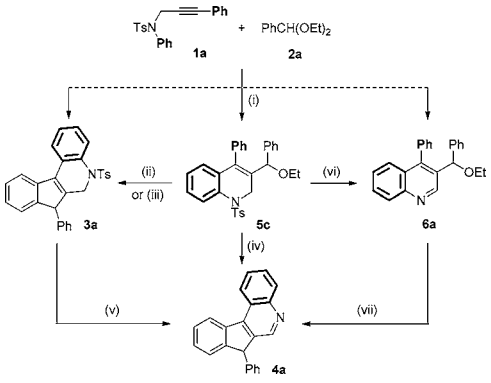


1 4

entry	1 / Ar (2)	yield[b]	entry	1 / Ar (2)	yield[b]
1	**1a**, X = H / Ph (**2a**)[c]	**4a**, 82%	12	**1h** / Ph (**2a**)[d]	**4l**, 75%
2	**1b**, X = Me / Ph (**2a**)[d]	**4b**, 74%	13	**1j**, X = Me / Ph (**2a**)[c]	**4m**, 84%
3	**1c**, X = OEt / Ph (**2a**)[d]	**4c**, 71%	14	**1r**, X = OMe/Ph (**2a**)[c]	**4n**, 81%
4	**1n** / Ph (**2a**)[c]	**4d**, 88%	15	**1i**, X = H / Ph (**2a**)[c]	**4o**, 96%
5	**1d** / Ph (**2a**)[c]	**4e**, 69%	16	**1k**, X = Me / Ph (**2a**)[c]	**4p**, 98%
6	**1e**, X = Cl / Ph (**2a**)[d]	**4f**, 70%	17	**1l**, X = H / Ph (**2a**)[d]	**4q**, 61%
7	**1f**, X = F / Ph (**2a**)[d]	**4g**, 67%	18	**1m**, X = Me / Ph (**2a**)[c]	**4r**, 67%
8	**1o**, X = Ac / Ph (**2a**)[c]	**4h**, 51%	19	**1a** / 4-MeC_6H_4 (**2b**)[d]	**4s**, 74%
9	**1p**, X = Cl / Ph (**2a**)[d]	**4i**, 88%	20	**1a** / 4-$MeOC_6H_4$ (**2l**)[d]	**4t**, 53%
10	**1q**, X = F / Ph (**2a**)[c]	**4j**, 70%	21	**1a** / 4-ClC_6H_4 (**2d**)[d]	**4u**, 60%
11	**1g** / Ph (**2a**)[d]	**4k**, 61%	22	**1a**/2-FC_6H_4 (**2h**)[d]	**4v**, 71%
			23	**1a**/2-naphthyl (**2k**)[d]	**4w**, 64%

[a]Conditions: **1** (0.3 mmol), **2** (0.6 mmol), FeX_3 (0.9 mmol), DCE (3 mL), 80 °C, N_2, 5 h. [b]Isolated yield. [c]Using $FeBr_3$. [d]Using $FeCl_3$.

Scheme 1. Control Experiments[a]



[a]Conditions: DCE as the solvent, N_2, 80 °C, 5 h; (i) 10 mol % $FeCl_3$ or $FeBr_3$, 27–28%; (ii) 30 mol % $FeCl_3$ or $FeBr_3$, 82–83%; (iii) 1 equiv $FeCl_3$ or $FeBr_3$, CH_2Cl_2, 25 °C, 18 h; (iv) 3 equiv $FeCl_3$ or $FeBr_3$, 64–65%; (v) 3 equiv $FeCl_3$ or $FeBr_3$, 58–72%; (vi) 10 equiv NaOMe, THF, reflux, 24 h, 33%; (vii) 3 equiv $FeCl_3$ or $FeBr_3$, 74–77%. THF = tetrahydrofuran.

Next, the protocol generality for the preparation of **4** was investigated under the optimal conditions (Table 3). Both $FeBr_3$ and $FeCl_3$ could promote the desired reactions. Substituents such as Me, OEt, Cl, F, and Ac were tolerated on the aryl groups of the NAr moieties (Table 3, entries 1–11). Unsubstituted **1a** and 2-Me- and 2-Cl-substituted substrates **1n** and **1p** efficiently underwent the reactions with **2a**, giving **4a** (82%), **4d** (88%), and **4i** (88%), respectively (Table 3, entries 1, 4, and 9). The 4- and 3-electron-withdrawing substituents rendered low yields for **4g** (67%), **4h** (51%), and **4k** (61%). A methyl or methoxy on the aryl group of a propargyl moiety of **1** did not exhibit obvious effect on the yields of **4l–n** (75–84%), whereas 3,5-dimethyls remarkably improved the formation of **4o** (96%) and **4p** (98%) (Table 3, entries 12–16). An electron-withdrawing substituent such as chloro on the aryl functional unit of a propargyl moiety of **1** deteriorated the reaction efficiency to give **4q** (61%) and **4r** (67%). Compound **1a** also reacted with other acetals to form the target products **4s–w** in 53–74% yields (Table 3, entries 19–23).

To probe the reaction mechanism, control experiments were conducted (Scheme 1). Compound **1a** reacted with **2a** in the presence of 10 mol % of $FeCl_3$ or $FeBr_3$ to afford 1-tosyl-1,2-dihydroquinoline **5c** (27–28%) via intermolecular carboarylation/cyclization, which further reacted under the stated conditions as shown in Tables 2 and 3 to give **3a** and **4a** in decent yields, respectively. Compound **3a** could be converted

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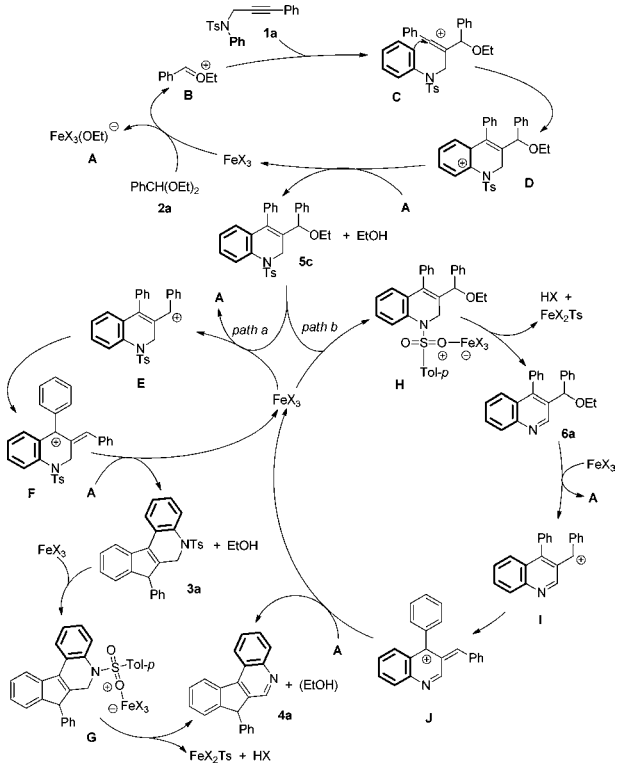
Scheme 2. Proposed Mechanism



to **4a** with $FeCl_3$ or $FeBr_3$ as the promoter. These results have revealed that both **5** and **3** can act as the intermediates to form **4** in the catalytic cycle. 4-Phenylquinoline (**6a**)[19] could also be utilized to access **4a**, further suggesting that species of types **5** and **6** may be generated as the reaction intermediates. It is noteworthy that **3a**, **4i**, and **5c** were structurally confirmed by X-ray crystallographic analysis (see the Supporting Information).

A plausible mechanism is proposed (Scheme 2). Acetal **2a** initially reacts with FeX_3 (X = Cl or Br) to form $FeX_3(OEt)^-$ anion (**A**) and oxocarbonium cation $PhCH{=}OEt^+$ (**B**).[17,18] Cation **B** interacts with propargylaniline **1a** to generate vinyl carbocation **C** stabilized by an aryl group, which undergoes intramolecular Friedel–Crafts reaction to yield **D**. Deprotonation of **D** by species **A** forms intermediate **5c** and ethanol, regenerating FeX_3. Following path a, species **5c** is converted to product **3a**[20] via the possible cationic species **E**[21] and **F**[18] assisted by FeX_3. Compound **3a** further reacts with FeX_3 to undergo detosylation/aromatization,[12] forming **4a**. Compound **5c** may also react with FeX_3 to form **6a** via species **H** by detosylation/aromatization (path b), which further undergoes carboarylation with FeX_3 to furnish **4a** and ethanol and regenerate the catalyst.

In summary, FeX_3-mediated tandem reactions of propargylanilines with aromatic aldehyde acetals form indeno[2,1-*c*]quinolines in good to excellent yields through carboarylation/cyclization under mild conditions. The present synthetic method provides a concise and nontoxic metal-mediated route to highly functionalized heteropolycyclic architectures.

■ ASSOCIATED CONTENT

Supporting Information

Complete experimental procedures and characterization data for the prepared compounds; X-ray crystallographic data for **3a**, **4i**, and **5c**. 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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