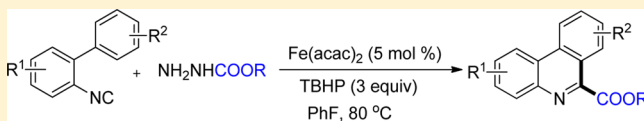


Radical Arylalkoxycarbonylation of 2-Isocyanobiphenyl with Carbazates: Dual C–C Bond Formation toward Phenanthridine-6-carboxylates

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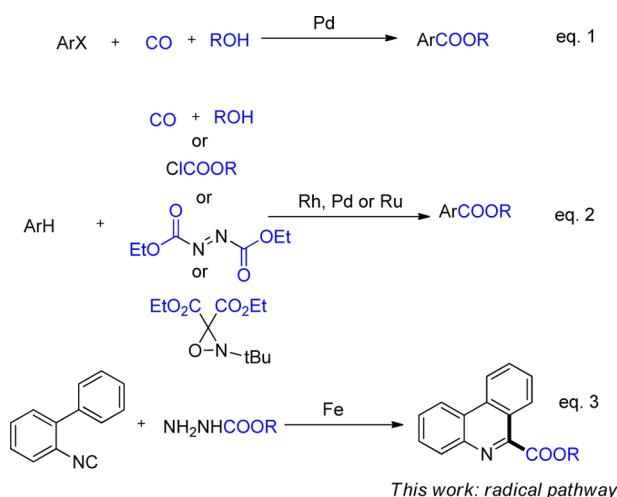
S Supporting Information

ABSTRACT: A sequential oxidative radical alkoxycarbonylation and aromatization of 2-isocyanobiphenyl with carbazates was developed to furnish phenanthridine-6-carboxylates. Various functional groups such as methoxy, chloro, fluoro, trifluoromethoxy, and trifluoromethyl groups were tolerated well under the reaction conditions. The sequential radical addition–cyclization strategy represents a practical route to access phenanthridine-6-carboxylates.



Carbonylation reactions are powerful tools for the construction of C–C bonds in synthetic chemistry.¹ Among these reactions, alkoxycarbonylation is highly valuable since it enables the direct introduction of an ester moiety into organic compounds.² Generally, CO and alcohols are applied as the source of the ester group in alkoxycarbonylation of ArX (Scheme 1, eq 1). Recently, great efforts have been dedicated to

Scheme 1. Alkoxycarbonylation of ArX or ArH



developing the efficient alkoxycarbonylation of C–H bonds (Scheme 1, eq 2).³ For example, Zhang developed a rhodium-catalyzed alkoxycarbonylation of sp² C–H bonds with CO toward esters.⁴ In 2012, Huang described a Pd-catalyzed alkoxycarbonylation of sp³ C–H bonds with CO.⁵ Other significant achievements in alkoxycarbonylation of C–H bonds

by carbamoyl chlorides,⁶ oxaziridine,⁷ and diethyl azodicarboxylate are well-documented.⁸

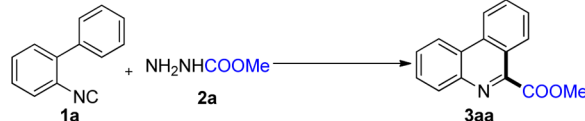
Radical chemistry has attracted much attention in organic synthesis in the past decades.⁹ However, the radical process for the preparation of esters is less developed.¹⁰ Yu reported the Pd-catalyzed oxidative ethoxycarbonylation of the aromatic C–H bond with diethyl azodicarboxylate by ethoxyacyl radicals.⁸ Carbazate was also applied to the construction of esters by alkoxycarbonyl radicals.¹¹ A sequential radical pathway is synthetically very promising since it could furnish short synthetic steps to access heterocycles.¹² Recently, isocyanides were developed to form 6-substituted phenanthridines that are abundant in natural products and pharmaceuticals,¹³ proceeding through the addition of a radical to the isonitrile to form an imidoyl radical, followed by intramolecular cyclization. For example, 6-arylation,¹⁴ 6-trifluoromethylation,¹⁵ 6-phosphorylation,¹⁶ 6-acylation,¹⁷ and 6-alkylation¹⁸ of 2-isocyanobiphenyl with different radical precursors were developed. Herein we report an oxidative alkoxycarbonylation of 2-isocyanobiphenyl with carbazates to provide phenanthridine-6-carboxylates by sequential radical addition–cyclization reactions (Scheme 1, eq 3).

Initially, the reaction of 2-isocyanobiphenyl (**1a**) with methyl carbazate (**2a**) in the presence of the radical initiator *tert*-butyl hydroperoxide (TBHP) with FeCl₂ as the catalyst was examined. To our delight, the desired methyl phenanthridine-6-carboxylate (**3aa**) was obtained in 51% yield (Table 1, entry 1). After screening of a series of catalysts, such as FeCl₂, Fe(acac)₂, FeCl₃, and CuI, Fe(acac)₂ was found to be the most efficient (Table 1, entry 2). Subsequently, we attempted to

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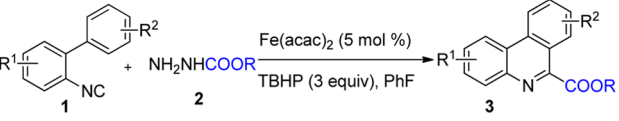
Table 1. Optimization of the Reaction Conditions^a


entry	[M]	radical initiator	solvent	yield (%)
1	FeCl ₂	TBHP	CH ₃ CN	51
2	Fe(acac) ₂	TBHP	CH ₃ CN	76
3	FeCl ₃	TBHP	CH ₃ CN	37
4	CuI	TBHP	CH ₃ CN	32
5	Fe(acac) ₂	DTBP	CH ₃ CN	26
6	Fe(acac) ₂	BPO	CH ₃ CN	33
7	Fe(acac) ₂	DCP	CH ₃ CN	8
8	Fe(acac) ₂	TBHP	DCE	83
9	Fe(acac) ₂	TBHP	PhF	93
10	Fe(acac) ₂	TBHP	PhCF ₃	77
11	Fe(acac) ₂	TBHP	benzene	70
12	Fe(acac) ₂	TBHP	PhCl	75
13	none	TBHP	PhF	33

^aReaction conditions: **1a** (0.2 mmol), **2a** (0.4 mmol), [M] (5 mol %), radical initiator (0.6 mmol), and solvent (1.5 mL) under a N₂ atmosphere for 12 h at 80 °C. TBHP was used as a 70% solution in water. DTBP = di-*tert*-butyl peroxide. BPO = benzoyl peroxide. DCP = dicumyl peroxide.

promote the yield by surveying solvents such as DCE, PhF, PhCF₃, PhCl, and benzene. Among the solvents screened, PhF was the best, providing **3aa** in 93% yield (Table 1, entry 9). Using DTBP, BPO, or DCP instead of TBHP resulted in low yields (Table 1, entries 5–7). The control experiment demonstrated that the radical reaction could also occur without catalyst but gave an unsatisfying result (Table 1, entry 13). Consequently, the optimum reaction conditions were determined to be Fe(acac)₂ (5 mol %) and TBHP (3 equiv) in PhF at 80 °C under N₂ (Table 1, entry 9).

To explore the substrate scope of this protocol, the optimized reaction conditions were applied to a series of 2-isocyanobiphenyl compounds. As shown in Table 2, various functional groups such as methoxy, chloro, fluoro, trifluoromethoxy, and trifluoromethyl groups were tolerated well under the present oxidative conditions, affording the products in good yields. We studied the effect of the substituents on the aromatic ring with the isocyanide group. As expected, the corresponding phenanthridine-6-carboxylates were obtained in good yields. Aromatic rings possessing electron-donating groups (**1b–d**; Table 2) gave higher yields than those with electron-withdrawing groups (**1f–j**; Table 2). Subsequently, the effects of substituents at the 4-position of the aromatic ring without the isocyanide group were investigated. The isocyanides **1k–m** bearing electron-donating groups provided the corresponding products in higher yields than did the electron-withdrawing analogues **1o** and **1p**. Notably, halogen groups were tolerable, which was suitable for potential further functionalization. 2-Isocyanobiphenyl bearing an *ortho* substituent revealed a lower reactivity due to the steric effect (Table 2, **3ra**). To investigate the regioselectivity of the cyclization, 2-isocyanobiphenyl **1s** bearing a *m*-methyl group was investigated, and it afforded a mixture of two regioisomers in a 2:1 ratio (Table 2, **3sa** + **3sa'**). As expected, when ethyl carbazate **2b** as an ethoxycarbonyl surrogate was employed, the arylethoxycarbonylation also ran well to afford ethyl phenanthridine-6-carboxylate (**3ab**) in good yield.

Table 2. Substrate Scope^a


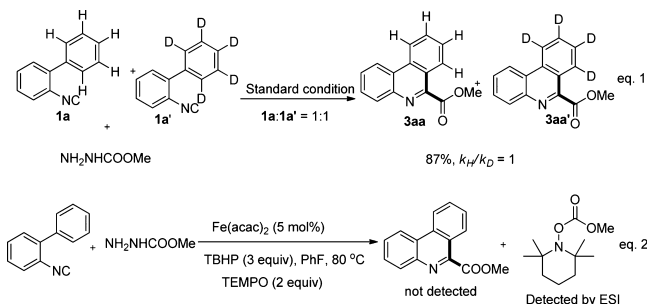
3aa , 93%	3ba , 81%	3ca , 83%
3da , 86%	3ea , 67%	3fa , 71%
3ga , 69%	3ha , 65%	3ia , 67%
3ja , 69%	3ka , 80%	3la , 82%
3ma , 83%	3na , 86%	3oa , 68%
3pa , 74%	3qa , 84%	3ra , 52%
3sa:3sa' = 2:1, ^b 66%		3ab , 78%

^aReaction conditions: **1** (0.2 mmol), **2** (0.4 mmol), Fe(acac)₂ (5 mol %), TBHP (0.6 mmol, 70% solution in water), and PhF (1.5 mL) under a N₂ atmosphere for 12 h at 80 °C. ^bThe ratio of isomers was determined by ¹H NMR analysis of the isolated products.

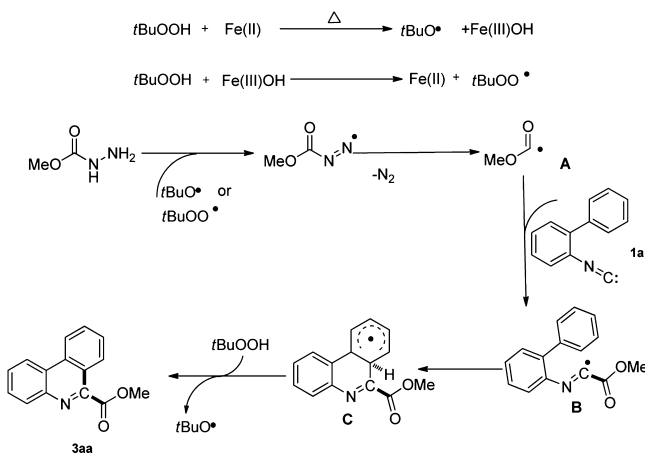
To have a better understanding of the difunctionalization of 2-isocyanobiphenyl, some mechanistic experiments were carried out. A 1:1 mixture of substrates **1a** and **1a'** was used to determine the intermolecular kinetic isotope effect, and no kinetic isotope effect (*k_H/k_D* = 1) was observed (Scheme 2, eq 1). This result revealed that the arylation step may be compatible with either the S_EAr mechanism or the free radical mechanism.¹⁹ When 2.0 equiv of 2,2,6,6-tetramethylpiperidine oxide (TEMPO) was added as a radical inhibitor, the desired product was not observed and the TEMPO–COOMe adduct was detected by ESI (Scheme 2, eq 2), providing evidence favoring the free radical mechanism.

On the basis of the above experimental results, a possible mechanism is proposed in Scheme 3. Initially, Fe(II)-assisted

Scheme 2. Preliminary Mechanistic Study



Scheme 3. Proposed Mechanism



homolysis of TBHP into *tert*-butoxy radical and *tert*-butylperoxy radical occurs. With the aid of Fe(II), the homolysis of TBHP into *tert*-butoxy radical may be accelerated by single-electron transfer along with the formation of an Fe(III) species.²⁰ Then, C–N bond cleavage of the carbamate forms alkoxycarbonyl radical A with the release of N₂ through stepwise hydrogen abstraction.¹¹ Then radical A attacks the N=C bond of 2-isocyanobiphenyl **1a** to form imidoyl radical B, which upon intramolecular cyclization with an aryl ring gives radical intermediate C. Finally, hydrogen abstraction of radical intermediate C takes place, providing the desired product **3aa**.

In summary, we have developed a novel sequential radical bimolecular C–C coupling of 2-isocyanobiphenyls with carbamates to provide phenanthridine-6-carboxylates. As the oxidant for this procedure, cheap and commercially available TBHP is used. The procedure involves dual C–C bond formation by sequential radical addition and cyclization reactions.

EXPERIMENTAL SECTION

General Information. NMR spectra were measured on 400 MHz NMR spectrometers (400 MHz for ¹H, 100 MHz for ¹³C, 376 MHz for ¹⁹F) using CDCl₃ as the solvent with tetramethylsilane (TMS) as the internal standard. Chemical shifts (δ) are given in parts per million relative to TMS, and coupling constants (J) are given in hertz. ¹³C NMR spectra were recorded at 100 MHz with complete proton decoupling. HRMS was performed on a TOF LC/MS equipped with an ESI probe operating in positive or negative ion mode. 2-Isocyanobiphenyl compounds were prepared according to the reported procedure.^{14a}

General Procedure for the Sequential Radical Coupling of 2-Isocyanobiphenyls with NH₂NHCOOMe. A mixture of 2-isocyanobiphenyl **1** (0.2 mmol), NH₂NHCOOMe (**2a**) (0.4 mmol, 36 mg), Fe(acac)₃ (5 mol %, 2.5 mg), TBHP (0.6 mmol, 70% solution in

H₂O), and PhF (1.5 mL) was added to a sealed tube. The sealed tube was evacuated and back-filled with N₂. The reaction mixture was vigorously stirred at 80 °C for 12 h. After the completion of the reaction, the solvent was evaporated under reduced pressure, and the residue was purified by flash column chromatography or preparative TLC on GF254 (petroleum/ethyl acetate) to afford the desired product **3**.

Methyl Phenanthridine-6-carboxylate (3aa).²¹ White solid (44 mg, 93%). ¹H NMR (CDCl₃, 400 MHz): δ 8.64–8.61 (m, 2H), 8.56 (d, J = 8.3 Hz, 1H), 8.28 (d, J = 7.8 Hz, 1H), 7.86 (d, J = 8.3 Hz, 1H), 7.79–7.69 (m, 3H), 4.12 (s, 3H). ¹³C NMR {1H} (CDCl₃, 100 MHz): δ 166.5, 150.3, 142.6, 133.4, 131.1, 130.9, 129.0, 128.7, 127.9, 127.3, 124.9, 123.5, 122.1, 122.0, 53.2.

Methyl 2-Methylphenanthridine-6-carboxylate (3ba). Green solid (40.6 mg, 81%), mp 162–164 °C. ¹H NMR (CDCl₃, 400 MHz): δ 8.64 (d, J = 8.4 Hz, 2H), 8.61 (d, J = 8.4 Hz, 1H), 8.33 (s, 1H), 8.18 (d, J = 8.4 Hz, 1H), 7.84 (t, J = 8.2 Hz, 1H), 7.70 (t, J = 8.1 Hz, 1H), 7.60–7.57 (m, 1H), 4.14 (s, 3H), 2.62 (s, 3H). ¹³C NMR {1H} (CDCl₃, 100 MHz): δ 166.5, 149.1, 140.7, 139.1, 133.1, 131.1, 130.9, 130.5, 127.8, 127.4, 124.9, 123.6, 122.1, 121.6, 53.2, 22.2. HRMS (ESI) *m/z*: calcd for C₁₆H₁₃NNaO₂ [M + Na]⁺ 274.0838, found 274.0840.

Methyl 3-Methylphenanthridine-6-carboxylate (3ca). White solid (41.6 mg, 83%), mp 81–83 °C. ¹H NMR (CDCl₃, 400 MHz): δ 8.61–8.56 (m, 2H), 8.42 (d, J = 8.4 Hz, 1H), 8.06 (s, 1H), 7.83 (t, J = 8.3 Hz, 1H), 7.67 (t, J = 8.3 Hz, 1H), 7.53 (d, J = 8.4 Hz, 1H), 4.14 (s, 3H), 2.57 (s, 3H). ¹³C NMR {1H} (CDCl₃, 100 MHz): δ 166.6, 150.2, 142.7, 139.3, 133.5, 131.1, 130.5, 130.4, 127.5, 127.3, 123.2, 122.6, 121.9, 121.8, 53.2, 21.5. HRMS (ESI) *m/z*: calcd for C₁₆H₁₃NNaO₂ [M + Na]⁺ 274.0838, found 274.0839.

Methyl 3-Methoxyphenanthridine-6-carboxylate (3da). Yellowish solid (45.9 mg, 86%), mp 110–112 °C. ¹H NMR (CDCl₃, 400 MHz): δ 8.60 (d, J = 8.3 Hz, 1H), 8.52 (d, J = 8.4 Hz, 1H), 8.45–8.42 (m, 1H), 7.81 (t, J = 8.1 Hz, 1H), 7.67–7.62 (m, 2H), 7.37–7.34 (m, 1H), 4.15 (s, 3H), 3.97 (s, 3H). ¹³C NMR {1H} (CDCl₃, 100 MHz): δ 166.5, 160.3, 150.5, 144.2, 133.7, 131.2, 127.4, 126.9, 123.2, 122.7, 121.6, 120.3, 119.1, 110.2, 55.7, 53.3. HRMS (ESI) *m/z*: calcd for C₁₆H₁₃NNaO₃ [M + Na]⁺ 290.0788, found 290.0787.

Methyl 2-(Trifluoromethoxy)phenanthridine-6-carboxylate (3ea). Brown liquid (43 mg, 67%). ¹H NMR (CDCl₃, 400 MHz): δ 8.65 (d, J = 8.0 Hz, 1H), 8.57 (d, J = 8.3 Hz, 1H), 8.37 (s, 1H), 8.32 (d, J = 9.0 Hz, 1H), 7.92 (t, J = 8.3 Hz, 1H), 7.78 (d, J = 8.2 Hz, 1H), 7.63 (d, J = 8.2 Hz, 1H), 4.15 (s, 3H). ¹³C NMR {1H} (CDCl₃, 100 MHz): δ 166.2, 150.8, 148.96, 148.94, 140.8, 133.0, 132.8, 131.6, 128.8, 127.6, 126.0, 123.6, 122.4, 122.2, 113.5, 53.3. ¹⁹F NMR (376 MHz, CDCl₃): δ –57.5. HRMS (ESI) *m/z*: calcd for C₁₆H₁₀F₃NNaO₃ [M + Na]⁺ 344.0505, found 344.0503.

Methyl 3-Fluorophenanthridine-6-carboxylate (3fa). Yellowish solid (36.2 mg, 71%), mp 128–130 °C. ¹H NMR (CDCl₃, 400 MHz): δ 8.57–8.50 (m, 3H), 7.93–7.90 (m, 1H), 7.86 (t, J = 8.2 Hz, 1H), 7.70 (t, J = 8.1 Hz, 1H), 7.50–7.45 (m, 1H), 4.15 (s, 3H). ¹³C NMR {1H} (CDCl₃, 100 MHz): δ 166.3, 162.7 (d, J_{C–F} = 247.8 Hz), 151.7, 143.8 (d, J_{C–F} = 11.9 Hz), 133.2, 131.6, 127.8, 127.5, 124.1 (d, J_{C–F} = 9.4 Hz), 123.0, 121.9, 121.6, 117.9 (d, J_{C–F} = 23.8 Hz), 115.2 (d, J_{C–F} = 20.6 Hz), 53.3. ¹⁹F NMR (376 MHz, CDCl₃): δ –110.9. HRMS (ESI) *m/z*: calcd for C₁₅H₁₀FNNaO₂ [M + Na]⁺ 278.0588, found 278.0586.

Methyl 2-Fluorophenanthridine-6-carboxylate (3ga). Yellowish solid (35.2 mg, 69%), mp 144–146 °C. ¹H NMR (CDCl₃, 400 MHz): δ 8.66 (d, J = 8.2 Hz, 1H), 8.50 (d, J = 8.3 Hz, 1H), 8.29–8.25 (m, 1H), 8.17–8.14 (m, 1H), 7.87 (d, J = 8.3 Hz, 1H), 7.75 (d, J = 8.3 Hz, 1H), 7.53–7.48 (m, 1H), 4.15 (s, 3H). ¹³C NMR {1H} (CDCl₃, 100 MHz): δ 166.3, 162.8 (d, J_{C–F} = 248.6 Hz), 149.4 (d, J_{C–F} = 2.9 Hz), 139.4 (d, J_{C–F} = 1.3 Hz), 133.3 (d, J_{C–F} = 9.4 Hz), 132.8 (d, J_{C–F} = 4.3 Hz), 131.2, 128.6, 127.5, 126.6 (d, J_{C–F} = 9.4 Hz), 123.5, 122.3, 118.2 (d, J_{C–F} = 24.4 Hz), 107.1 (d, J_{C–F} = 23.4 Hz), 53.3. ¹⁹F NMR (376 MHz, CDCl₃): δ –109.4. HRMS (ESI) *m/z*: calcd for C₁₅H₁₀FNNaO₂ [M + Na]⁺ 278.0588, found 278.0589.

Methyl 2-Chlorophenanthridine-6-carboxylate (3ha). White solid (35.2 mg, 65%), mp 132–133 °C. ¹H NMR (CDCl₃, 400 MHz): δ 8.62 (d, J = 8.3 Hz, 1H), 8.52 (d, J = 8.3 Hz, 1H), 8.50 (s, 1H), 8.19

(d, $J = 8.8$ Hz, 1H), 7.87 (t, $J = 8.3$ Hz, 1H), 7.74 (t, $J = 8.2$ Hz, 1H), 7.71–7.68 (m, 1H), 4.15 (s, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 166.2, 150.4, 140.9, 134.9, 132.4, 132.3, 131.5, 129.7, 128.6, 127.5, 125.9, 123.7, 122.2, 121.8, 53.3. HRMS (ESI) m/z : calcd for C₁₅H₁₀ClNNaO₂ [M + Na]⁺ 294.0292, found 294.0289.

Methyl 3-(Trifluoromethyl)phenanthridine-6-carboxylate (3ia). Semisolid (40.9 mg, 67%). ^1H NMR (CDCl₃, 400 MHz): δ 8.64–8.61 (m, 3H), 8.57 (s, 1H), 7.94–7.89 (m, 2H), 7.81–7.77 (m, 1H), 4.16 (s, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 166.0, 151.7, 141.8, 132.6, 131.8, 130.9 (q, $J_{\text{C-F}} = 32.9$ Hz), 129.1, 128.4 (q, $J_{\text{C-F}} = 4.1$ Hz), 127.6, 127.1, 124.4 (q, $J_{\text{C-F}} = 3.1$ Hz), 124.0, 123.2, 122.5, 53.4. ^{19}F NMR (376 MHz, CDCl₃): δ –62.4. HRMS (ESI) m/z : calcd for C₁₆H₁₀F₃NNaO₂ [M + Na]⁺ 328.0556, found 328.0558.

Methyl 2-(Trifluoromethyl)phenanthridine-6-carboxylate (3ja). White solid (42 mg, 69%), mp 112–114 °C. ^1H NMR (CDCl₃, 400 MHz): δ 8.73 (s, 1H), 8.54 (d, $J = 8.3$ Hz, 1H), 8.49 (d, $J = 8.3$ Hz, 1H), 8.27 (d, $J = 8.5$ Hz, 1H), 7.88–7.81 (m, 2H), 7.70–7.66 (m, 1H), 4.07 (s, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 166.1, 152.5, 143.9, 133.1, 131.9, 131.8, 130.2 (q, $J_{\text{C-F}} = 32.7$ Hz), 128.8, 127.6, 125.4, 125.0 (q, $J_{\text{C-F}} = 3.1$ Hz), 124.5, 123.6, 122.7, 122.1, 119.9 (q, $J_{\text{C-F}} = 4.2$ Hz), 53.4. ^{19}F NMR (376 MHz, CDCl₃): δ –62.0. HRMS (ESI) m/z : calcd for C₁₆H₁₀F₃NNaO₂ [M + Na]⁺ 328.0556, found 328.0555.

Methyl 8-Methylphenanthridine-6-carboxylate (3ka). White solid (40.2 mg, 80%), mp 80–81 °C. ^1H NMR (CDCl₃, 400 MHz): δ 8.53–8.50 (m, 2H), 8.36 (s, 1H), 8.27–8.25 (m, 1H), 7.75–7.66 (m, 3H), 4.15 (s, 3H), 2.58 (s, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 166.6, 150.1, 142.2, 138.1, 133.0, 131.4, 130.8, 128.6, 126.6, 125.0, 123.6, 122.2, 121.9, 53.2, 21.9. HRMS (ESI) m/z : calcd for C₁₆H₁₃NNaO₂ [M + Na]⁺ 274.0838, found 274.0840.

Methyl 8-Methoxyphenanthridine-6-carboxylate (3la). Yellow solid (43.6 mg, 82%), mp 203–205 °C. ^1H NMR (CDCl₃, 400 MHz): δ 8.56–8.54 (m, 1H), 8.50–8.48 (m, 1H), 8.28–8.25 (m, 1H), 8.15 (s, 1H), 7.72–7.70 (m, 2H), 7.51–7.48 (m, 1H), 4.15 (s, 3H), 3.99 (s, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 166.6, 159.1, 148.5, 141.8, 131.0, 128.9, 128.1, 125.3, 125.2, 123.7, 122.5, 121.6, 106.7, 55.6, 53.2. HRMS (ESI) m/z : calcd for C₁₆H₁₃NNaO₃ [M + Na]⁺ 290.0788, found 290.0786.

Methyl 8-(tert-Butyl)phenanthridine-6-carboxylate (3ma). Brown liquid (48.6 mg, 83%). ^1H NMR (CDCl₃, 400 MHz): δ 8.65–8.64 (m, 1H), 8.59–8.53 (m, 2H), 8.29–8.26 (m, 1H), 7.97–7.95 (m, 1H), 7.76–7.69 (m, 2H), 4.16 (s, 3H), 1.46 (s, 9H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 166.7, 151.1, 150.2, 142.4, 131.4, 130.9, 129.7, 128.7, 125.0, 123.6, 122.8, 122.0, 121.9, 53.2, 35.2, 31.2. HRMS (ESI) m/z : calcd for C₁₉H₁₉NNaO₂ [M + Na]⁺ 316.1308, found 316.1305.

Methyl 8-Phenylphenanthridine-6-carboxylate (3na). Yellowish solid (53.8 mg, 86%), mp 136–138 °C. ^1H NMR (CDCl₃, 400 MHz): δ 8.86 (s, 1H), 8.67 (d, $J = 8.6$ Hz, 1H), 8.56 (d, $J = 8.4$ Hz, 1H), 8.29 (d, $J = 7.4$ Hz, 1H), 8.10 (d, $J = 8.6$ Hz, 1H), 7.77–7.73 (m, 4H), 7.51 (t, $J = 7.4$ Hz, 2H), 7.41 (t, $J = 7.3$ Hz, 1H), 4.16 (s, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 166.5, 150.2, 142.5, 140.7, 140.0, 132.4, 131.0, 130.5, 129.0, 128.9, 128.0, 127.5, 125.3, 124.8, 124.0, 122.8, 122.1, 53.3. HRMS (ESI) m/z : calcd for C₂₁H₁₅NNaO₂ [M + Na]⁺ 336.0995, found 336.0994.

Methyl 8-Chlorophenanthridine-6-carboxylate (3oa). White solid (36.8 mg, 68%), mp 126–128 °C. ^1H NMR (CDCl₃, 400 MHz): δ 8.81 (d, $J = 8.3$ Hz, 1H), 8.51 (d, $J = 8.3$ Hz, 1H), 8.49 (s, 1H), 8.20 (d, $J = 8.8$ Hz, 1H), 7.87 (d, $J = 8.3$ Hz, 1H), 7.74 (d, $J = 8.3$ Hz, 1H), 7.41–7.68 (m, 1H), 4.15 (s, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 166.5, 150.3, 140.7, 134.9, 132.4, 132.2, 131.6, 129.8, 128.6, 127.5, 125.9, 123.6, 122.1, 121.7, 53.3. HRMS (ESI) m/z : calcd for C₁₅H₁₀ClNNaO₂ [M + Na]⁺ 294.0292, found 294.0290.

Methyl 8-(Trifluoromethyl)phenanthridine-6-carboxylate (3pa). Yellowish solid (45 mg, 74%), mp 90–92 °C. ^1H NMR (CDCl₃, 400 MHz): δ 9.04 (s, 1H), 8.69 (d, $J = 8.7$ Hz, 1H), 8.54 (d, $J = 8.0$ Hz, 1H), 8.30 (d, $J = 8.0$ Hz, 1H), 8.03 (d, $J = 8.7$ Hz, 1H), 7.86–7.76 (m, 2H), 4.17 (s, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 165.9, 149.4, 143.1, 135.4, 131.2, 130.2, 129.7 (q, $J_{\text{C-F}} = 32.7$ Hz), 129.4, 126.9 (q, $J_{\text{C-F}} = 3.1$ Hz), 125.2 (q, $J_{\text{C-F}} = 4.5$ Hz), 124.0, 123.2, 122.9, 122.5, 122.4, 53.4. ^{19}F NMR (376 MHz, CDCl₃): δ –62.3. HRMS

(ESI) m/z : calcd for C₁₆H₁₀F₃NNaO₂ [M + Na]⁺ 328.0556, found 328.0556.

Methyl Benzo[il]phenanthridine-5-carboxylate (3qa). Colorless liquid (48.2 mg, 84%). ^1H NMR (CDCl₃, 400 MHz): δ 8.51 (d, $J = 8.3$ Hz, 1H), 8.46 (d, $J = 9.0$ Hz, 1H), 8.31 (d, $J = 8.3$ Hz, 1H), 8.26 (d, $J = 8.3$ Hz, 1H), 8.05 (d, $J = 9.0$ Hz, 1H), 7.90 (d, $J = 8.4$ Hz, 1H), 7.75 (t, $J = 8.2$ Hz, 1H), 7.69–7.58 (m, 3H), 4.14 (s, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 169.9, 150.4, 143.3, 133.9, 132.8, 132.6, 130.1, 129.4, 129.1, 128.5, 128.1, 127.6, 127.1, 124.7, 124.4, 122.6, 119.7, 119.0, 53.4. HRMS (ESI) m/z : calcd for C₁₉H₁₃NNaO₂ [M + Na]⁺ 310.0838, found 310.0837.

Methyl 10-Chlorophenanthridine-6-carboxylate (3ra). White solid (28.1 mg, 52%), mp 109–111 °C. ^1H NMR (CDCl₃, 400 MHz): δ 9.83 (d, $J = 8.6$ Hz, 1H), 8.47 (d, $J = 8.2$ Hz, 1H), 8.31 (d, $J = 8.0$ Hz, 1H), 7.96 (d, $J = 7.7$ Hz, 1H), 7.87–7.82 (m, 1H), 7.79–7.75 (m, 1H), 7.63 (d, $J = 8.0$ Hz, 1H), 4.16 (s, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 166.6, 151.1, 143.7, 135.0, 131.5, 131.0, 130.3, 129.5, 128.2, 127.7, 126.7, 126.4, 125.7, 123.9, 53.4. HRMS (ESI) m/z : calcd for C₁₅H₁₀ClNNaO₂ [M + Na]⁺ 294.0292, found 294.0294.

Methyl 7-Methylphenanthridine-6-carboxylate (3sa) and Methyl 9-Methylphenanthridine-6-carboxylate (3sa'). Brown liquid (33 mg, 66%). ^1H NMR (CDCl₃, 400 MHz): δ 8.55–8.51 (m, 3H), 8.41 (s, 0.51H), 8.26 (d, $J = 8.3$ Hz, 0.5H), 8.19 (d, $J = 8.3$ Hz, 1H), 7.77–7.66 (m, 4H), 7.53 (d, $J = 8.5$ Hz, 0.59H), 7.49 (d, $J = 7.2$ Hz, 1.12H), 4.24 (s, 1.45H), 4.11 (s, 2.9H), 2.72 (s, 3H), 2.63 (s, 1.5H). HRMS (ESI) m/z : calcd for C₁₆H₁₃NNaO₂ [M + Na]⁺ 274.0838, found 274.0837.

Ethyl Phenanthridine-6-carboxylate (3ab).²¹ Compound 3ab was obtained using 1a and NH₂NHCOOEt (2b). White solid (39.1 mg, 78%). ^1H NMR (CDCl₃, 400 MHz): δ 8.63 (d, $J = 8.3$ Hz, 1H), 8.57–8.52 (m, 2H), 8.29 (d, $J = 7.8$ Hz, 1H), 7.86 (t, $J = 8.2$ Hz, 1H), 7.78–7.69 (m, 3H), 4.64 (q, $J = 7.2$ Hz, 2H), 1.53 (t, $J = 7.2$ Hz, 3H). ^{13}C NMR {1H} (CDCl₃, 100 MHz): δ 166.2, 151.0, 142.4, 133.4, 131.3, 130.7, 129.1, 128.6, 127.9, 127.3, 124.8, 123.3, 122.2, 122.0, 62.5, 14.4.

Intermolecular Competition Experiment with Isotopically Labeled 1a'. A mixture of 2-isocyanobiaryl 1a (0.1 mmol) and the labeled analogue 1a' (0.1 mmol), NH₂NHCOOMe 2a (0.4 mmol), Fe(acac)₃ (5 mol %, 2.5 mg), TBHP (0.6 mmol, 70% in H₂O), and PhF (1.5 mL) was added to a sealed tube, which was evacuated and back-filled with N₂. The reaction mixture was vigorously stirred at 80 °C for 12 h. After the completion of the reaction, the solvent was evaporated under reduced pressure, and the residue was purified by flash column chromatography on silica gel or preparative TLC on GF254 to afford the desired products 3aa and 3aa'. ^1H NMR (CDCl₃, 400 MHz): δ 8.67–8.62 (m, 1H), 8.59 (d, $J = 7.7$ Hz, 1H), 7.88 (d, $J = 8.2$ Hz, 0.51H), 7.80–7.71 (m, 2.52H), 4.15 (s, 3H).

■ ASSOCIATED CONTENT

Supporting Information

^1H and ^{13}C NMR spectra of compounds 3aa–sa and 3ab and ^{19}F NMR spectra of compounds 3ea, 3fa, 3ga, 3ia, 3ja, and 3pa. 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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