



Synthetic Communications An International Journal for Rapid Communication of Synthetic Organic Chemistry

ISSN: 0039-7911 (Print) 1532-2432 (Online) Journal homepage: http://www.tandfonline.com/loi/lsyc20

Facial strategy for radical species through Ag(I)mediated oxidation of the alkyl trifluoroborates

Siyi Ding, Shaopeng Tian, Yuzhen Zhao, Qiang Ma, Min Zhu, Huaping Ren, Kexuan Li & Zongcheng Miao

To cite this article: Siyi Ding, Shaopeng Tian, Yuzhen Zhao, Qiang Ma, Min Zhu, Huaping Ren, Kexuan Li & Zongcheng Miao (2018): Facial strategy for radical species through Ag(I)-mediated oxidation of the alkyl trifluoroborates, Synthetic Communications, DOI: <u>10.1080/00397911.2018.1431280</u>

To link to this article: https://doi.org/10.1080/00397911.2018.1431280

+

View supplementary material \square



Published online: 09 Mar 2018.

_	
Γ	
	6
-	

Submit your article to this journal \square

Article views: 3



View related articles 🗹



View Crossmark data 🗹



Check for updates

Facial strategy for radical species through Ag(I)-mediated oxidation of the alkyl trifluoroborates

Siyi Ding (), Shaopeng Tian, Yuzhen Zhao, Qiang Ma, Min Zhu, Huaping Ren, Kexuan Li, and Zongcheng Miao

Key Laboratory of Organic Polymer Photoelectric Materials, School of Science, Xijing University, Xi'an, Shaanxi, China

ABSTRACT

A rapid and highly efficient method for the radical formation using potassium alkylfluoroborates as radical precursor is devised and developed which conducts under relatively mild condition using silver (I) oxide as the oxidant. The observed silver mirror phenomenon hints at the fact that Ag_2O is the real oxidant. This approach effectively overcomes the drawbacks-stringent reaction conditions and poor tolerance of a variety of functional groups.

GRAPHICAL ABSTRACT



ARTICLE HISTORY Received 18 September 2017

KEYWORDS Alkyl radical; alkyl trifluoroborates; silver(I)-mediated oxidation

Introduction

Radical chemistry has attracted special research interest and has found widespread applications in medicinal chemistry, agrochemicals, and material science.^[1] Over the past few years, radical reactions have gradually become versatile and useful synthetic methods for the construction of carbon–carbon bond.^[2] By virtue of the tandem radical reactions, including radical addition or cyclization of functionalized alkenes,^[3] various heterocycles can be obtained in convenient pathways.

Organometallic compounds, such as organolithium reagents and Grignard reagents, can be oxidized to their relevant radicals.^[4,5] Using organometallic compounds as the radical precursors, however, we face several drawbacks because of their high reactivity and their sensitivity to air and moisture.^[6] Another critical defect for the wide application of such organometallic compounds is poor tolerance of many functional groups. To overcome these limitations, the top priority is to find another softer organometallic reagent. Organotrifluoroborates, because of their lack of the empty *p*-orbitals, are less sensitive to numerous organic reagents than their boronic acid analogues. This important characteristic facilitates their ease of handling, stability and robustness under harsh reaction conditions. Recently,

CONTACT Zongcheng Miao 🖾 miaozongcheng@xijing.edu.cn 🝙 Key Laboratory of Organic Polymer Photoelectric Materials, School of Science, Xijing University, Xi'an, Shaanxi 710123, China.

(3) Supplemental data (full experimental details and ¹HNMR, ¹³CNMR, and HRMS for all compounds) can be accessed on the publisher's website.

^{© 2018} Taylor & Francis



Scheme 1. Approaches toward the radical formation using alkyl trifluoroborate as the precursors.

potassium organotrifluoroborates have been used widely in as nucleophiles transitionmetal-catalyzed reactions.^[7] As is the case with boronic acids, potassium organotrifluoroborates also can serve as radical precursors. Thus far, the generation of carbon-centered radicals from alkyl potassium organotrifluoroborates (alkyl BF₃K) has been performed by stoichiometric or excess amount of oxidants (Scheme 1a). In 2010, Fensterbank and colleagues reported that alkylBF₃K served as radical precursors under oxidative conditions using copper(II) acetate (Cu(OAc)₂) or copper(II) chloride (CuCl₂) and 2,2,6, 6-tetramethylpiperidinooxy (TEMPO).^[8] This method was compatible with primary and tertiary substrates. The following year, Molander's group put forward another oxidative system^[9] using 2.5 equiv. of manganese (III) acetate in the presence of trifluoroacetic acid in a 1:1 mixture of acetic acid and water. Two years later, Yu's finding hinted at the fact that silver(I) carbonate played an essential role in the generation of free alkyl radicals.^[10] Moreover, the formed alkyl radicals were successfully applied in the Palladium(II) catalyzed ortho- $C(sp^2)$ -H alkylation reactions. Baran reported that radical reactions could be induced by a combination of a catalytic amount of silver(I) nitrate and an excess amount of potassium persulfate as co-oxidant (Scheme 1b).^[11]

Alternatively, a visible-light-driven single-electron tranmetalation photoredox catalysis provides a facial and efficient access to carbon centered radicals through oxidation of organotrifluoroborates (Scheme 1c). This strategy recently has attracted significant interest of synthetic chemists and has been accepted widely as an effective way to generate radical species.^[12] Molander and colleagues developed a dual catalytic system^[12d,12e,12g] containing nickel salt along with photocatalyst, which allowed for the efficient use of alkyltrifluoroborates in cross-coupling reactions under relatively mild conditions. The alkyl radicals, which were generated through on oxidation process in the presence of visible-light photoredox catalyst, easily underwent facial single-electron transmetalation onto a nickel catalyst and then gave the target products through a reductive elimination process. The previously

mentioned methods, however, still have some shortcomings, including, for example, the formation of large amounts of metallic wastes, harsh reaction conditions, poor tolerance of many different functional groups, the requirement of special equipments and expensive photoredox catalysts. Therefore, it is essential to develop a more efficient method for the generation of free radicals.

Results and discussion

Initially, to probe our design, we examined the reactivity of phenylpropyl trifluoroborate **1a**, embedding in our memory that the phenylpropyl radical should be the classical alkyl radical. The generated radials were then trapped by TEMPO, affording **2a** and showing crucial evidence for the existence of the radical intermediate. We first operated reactions with $Cu(OAc)_2$ as the oxidant, together with 1.0 equiv. of silver oxide (Ag₂O) as the co-oxidant. The reactions were easily monitored by gas chromatography-mass spectrometry (GC-MS) and thin-layer chromatography (TLC). Notably, a good yield of **2a** was detected in toluene/water (50:1) mixture (Table 1, entry 2). Furthermore, adding a small amount of water was highly beneficial to guarantee a good yield (Table 1, entry 13), suggesting the possible role of water in keeping the alkylboron species in the reactive boronic acid form. Although the protic solvent, such as methanol, was not suitable for this reaction (Table 1, entry 5), polar solvents together with trace distilled water provided worse results (Table 1, entry 5). In the toluene/water system, each kind of copper salts together with Ag₂O gave a similar yield (for more details, see supplemental information).

	BF ₃ K	oxidant/co-oxidant TEMPO		
		Solvent T°C, th		
	1a	2a		
Entry	Catalyst (0.2 equiv.)	Oxidant (1.0 equiv.)	Solvent	2a ^d yield [%]
1	Cu(OAc) ₂	Ag ₂ O	Tol ^b	ND
2	$Cu(OAc)_{2}$	Ag ₂ O	Tol ^c	98
3	Cu(OAc) ₂	Ag ₂ O	DCM ^c	65
4	Cu(OAc) ₂	Ag ₂ O	EA ^c	26
5	Cu(OAc) ₂	Ag ₂ O	MeOH ^c	ND
6	Cu(OAc) ₂	Ag ₂ O	DMF ^c	30
7	Cu(OAc) ₂	Ag ₂ O	MeCN ^c	42
8	Cu(OAc) ₂	MnO ₂	Tol ^c	ND
9	Cu(OAc) ₂	Mn(OAc) ₂	Tol ^c	ND
10	Cu(OAc) ₂	AgNO ₃	Tol ^c	ND
11	-	Cu(OAc) ₂	Tol ^c	ND
12	-	Ag ₂ O	Tol ^c	98(95) ^g
13	-	Ag ₂ O	Tol ^b	ND
14	-	Ag ₂ O	Tol ^{c,e}	8
15	-	OcpA	Tol ^{c,f}	ND

 Table 1.
 Oxidation of phenylpropyl trifluoroborate 1a.

^{*a*}Reaction conditions: RBF₃K (0.1 mmol, 1.0 equiv.), TEMPO (0.1 mmol, 1.0 equiv.), Ag_2O (0.1 mmol, 1.0 equiv.). ^{*b*}The reaction was conducted without addition of distilled water.

^cThe reaction was conducted with addition of distilled water(20 µL).

^dNMR yield, 1,3,5-trimethoxyl benzene as the internal standard reagent.

^eThe reaction was run under air.

^fThe reaction was conducted under oxygen atmosphere.

^{*g*}Yield of the isolated product, purified by column chromatography.

ND, not determined; DCM, dichloromethane; DMF, dimethylformamide; TEMPO, 2,2,6,6-tetramethyl-1-piperidinyloxy, free radical.

Interestingly, a similar result could be obtained without copper salts (Table 1, entry 12). Using other oxidants instead of Ag_2O , we could not observe any radical adduct by TLC or GC-MS (Table 1, entries 8–10). These findings proved that Ag_2O was an effective oxidant to produce the alkyl radicals in high yield. $Cu(OAc)_2$ was totally unreactive under the current conditions (Table 1, entries 11 and 12). This is remarkable because $Cu(OAc)_2$ has been proved to be an effective oxidant of alkyl trifluoroborates in other different conditions.^[8] Attempts to run this reaction under an air or oxygen atmosphere resulted in very low yield (Table 1, entries 14 and 15). Increasing or lowering the reaction temperature was of no advantage to these reactions (for more details, see supplemental information). Finally, we ran the model reaction at a 5.0 mmol scale using **1a** as the starting materials, and the isolated yield of the aim product was 86%, compared with 95% at the 0.1 mmol scale and 93% at the 1.0 mmol scale, respectively (for more details, see supplemental information).

Having defined an appropriate set of reaction conditions, we briefly investigated the scope of alkyl trifluoroborates (Scheme 2). Notably, benzyl trifluoroborate (1e) could be easily oxidized to generate the benzyl radical, which was trapped by TEMPO. Primary alkyl trifluoroborates bearing functional groups, such as ester (1j, 1k, and 1l) and even ketone (1i), were suitable substrates. In addition, alkyl trifluoroborates with heteroarene moieties were compatible (1m and 1n). Note that the alkyl moiety with bromo- or chloro-atoms (1c and 1d) remained intact under these conditions, demonstrating the mild nature of the reaction condition. When we used branched alkyl trifluoroborates, we obtained a moderate yield, which was not sensitive to steric hindrance (1g, 1h, and 11). Furthermore, secondary alkyl-trifluoroborates (10 and 1p), and tertiary alkyltrifluoroborate (1q) were also viable substrates under the current conditions, and they could be quantitatively oxidized to form the relevant radicals. After the process was completed, silver mirror formed on the surface of the reactor, which was so difficult to remove that we had to use nitric acid to get rid of the silver(0). We ran all of these reactions at a 1.0 mmol scale under the standard reaction conditions with excellent isolated yield, which are showed in the brackets.

Following these theoretical knowledge,^[7] we think that a single-electron transfer from the copper-catalyst generates a transient radical and a low-valent copper species, which can be oxidized by Ag_2O to re-participate in the process (Scheme 3a). On the basis of our experimental results, however, we put forward a more reasonable mechanism (Scheme 3b). A single electron that is transferred from the oxidant Ag_2O can generate alkyl radical, and is accompanied by the formation of boron trifluoride. Then, TEMPO can trap the alkyl radical to get the adduct.

Thus far, we have successfully applied this new radical formation strategy in a boron-selective oxidative cross-coupling reaction^[13] using arylboronic acids and alkyltri-fluoroborates as the coupling partners (Scheme 4). The carbon-centered radical, generated from the Ag₂O-mediated oxidative process, undergoes the single-electron transmetalation onto the aryl-Cu(II)X species, which was formed through transmetalation of the aryl boro-nic acids to the copper catalyst, and then reductive elimination occurs from the reactive intermediate ArCu(III)RX to produce the desired cross-coupling product. This strategy provides us a new way to construct C–C bond. Primary and secondary alkyltrifluoroborates can successfully participate in the current reaction. Fortunately, the bromine group, which may not be compatible under the reaction conditions containing the organometallic



[a] Yield of the isolated product under the reaction condition: RBF_3K (0.1 mmol, 1.0 eq.), TEMPO (0.1 mmol, 1.0 eq.), Ag_2O (0.1 mmol, 1.0 eq.); [b] Yield of the isolated product under the reaction condition: RBF_3K (1.0 mmol, 1.0 eq.), TEMPO (1.0 mmol, 1.0 eq.), Ag_2O (1.0 mmol, 1.0 eq.);

Scheme 2. Oxidation of potassium alkyl trifluoroborates. Note: TEMPO, 2,2,6,6-tetramethylpiperidinooxy.

compounds, is also viable substrate with moderate yield. Under the same condition, the benzylic alkyltrifluoroborate **1e** can be oxidized to form its corresponding benzyl radical, which has special structure and high reactivity, and then lead to relatively low yield.

Encouraged by these preliminary results, we explored more meaningful application from the synthetic point. Aryl isonitriles are another well-established radical acceptor, which are isoelectronic with carbon monoxide, and they can undergo insertion reaction to provide *N*-containing heterocycles that are important substrate present in many natural products with different biological activities.^[14] In practice, using the model substrate **1f** under this reaction condition with the addition of 2-isocyano-1,1'-biphenyl, we found



Scheme 3. (a) Proposed mechanism and (b) revised mechanism.

the phenanthridine **4f** was formed in a moderate yield. The result obtained with Ag_2O is depicted in Scheme 5. This is another strategy for the new $C(sp^2)-C(sp^3)$ bond formation, which might be compatible with various functionalized groups. These results suggest the need for elaboration and will be reported in due course.



Reaction conditions: RBF₃K (0.2 mmol, 1.0 equiv.), 4-methoxylphenyl boronic acid (0.3 mmol, 1.5 equiv.), Cu(OAc)₂ (0.02 mmol, 0.1 equiv.), Ag₂O (0.4 mmol, 2.0 equiv.), CH₃ONa (0.2 mmol, 1.0 equiv.), toluene (2.0 mL), distilled water (40 μ l), room temperature, 10 min.

Scheme 4. Application in the copper-catalyzed boron-selective C(sp₂)–C(sp₃) oxidative cross-coupling reactions between arylboronic acids and alkyltrifluoroborates.



Scheme 5. Application in the insertion reaction to construct the phenanthridine.

Conclusion

In summary, we discovered an Ag₂O-oxidized method to form alkyl radicals using potassium alkyl-trifluoroborates as the precursors. This reaction is interesting and potentially advantageous. For the radical precursors, in comparison with other organometallic reagents, organoboronic acid derivatives are more readily available, stable to air and moisture, and compatible with many functional groups. Moreover, this new strategy features excellent product selectivity, a short reaction time, mild reaction conditions, simple operation, and broad functional group tolerance. In comparison with conventional strategies, the current reaction requires an additional step to obtain an organoboron reactant using the corresponding halide as the starting materials. Nevertheless, taking into consideration that many shelf-stable alkyl-organoboron derivatives are already available in the market, this reaction should be of great use in facilitating small-molecule array synthesis. Although the complete mechanism remains unclear, this silver(I) oxidized method can be used in many different kinds of organic reactions, including radical addition or cyclization of functionalized alkenes. Its application prospect in organic chemistry and functional material chemistry is very broad and quite optimistic. Research in this area is ongoing in our lab.

Experimental

General

Unless otherwise noted, all reactions were performed in a flame-dried, sealed Schlenk reaction tube under nitrogen atmosphere.

Analytical thin-layer chromatography was performed on glass plates coated with 0.25 mm 230–400 mesh silica gel containing a fluorescent indicator (Merck). Visualization was accomplished by exposure to a UV lamp, and/or treatment with a solution of KMnO₄ or a solution of phosphomolybdic acid followed by brief heating with a heating gun. Most of the products in this article are compatible with standard silica gel chromatography. Column chromatography was performed on silica gel 60N (spherical and neutral, 140–325 mesh) using standard methods.

Structural analysis

NMR spectra were measured on a Bruker Avance-400 spectrometer and chemical shifts (δ) are reported in parts per million (ppm). ¹H NMR spectra were recorded at 400 MHz in NMR solvents (CDCl₃, Acetone-*d*₆, DMSO-*d*₆) and referenced internally to corresponding solvent resonance, and ¹³C NMR spectra were recorded at 100 MHz and referenced to corresponding solvent resonance, Carbons bearing boron substituents were generally not observed due to quadrupolar relaxation. Coupling constants are reported in Hz with

8 🔄 S. DING ET AL.

multiplicities denoted as s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), and br (broad). Infrared spectra were collected on a Thermo Fisher Nicolet 6700 FI-IR spectrometer using attenuated total reflectance method. Absorption maxima are reported in wavenumbers (cm⁻¹). High resolution mass spectra (HRMS) were obtained on a Bruker Apex IV FTMS spectrometer or an Agilent 6224 LC/MS TOF spectrometer.

Materials

Commercial reagents were purchased from J&K, Energy, Sigma-Aldrich, Alfa Aesar, Acros Organics, Strem Chemicals, TCI and used as received unless otherwise stated. Solvents, including hexane, THF, Et_2O , toluene, were purified by distillation over sodium, and stored under N_2 .

General procedure

In air, the potassium alkyltrifluoroborate (1.0 equiv.), Ag₂O (1.0 equiv.), and TEMPO (1.0 equiv.) were sequentially weighed and added to a screw-capped Schenk tube containing a magnetic stir bar. The vessel was evacuated and refilled with nitrogen for three times. Toluene (10.0 mL mmol⁻¹) and distilled water (200 μ L mmol⁻¹) were added in turn under N₂ atmosphere using syringes through a septum which was temporarily used to replace the screw cap. The reaction mixture was then vigorously stirred at room temperature for the indicated time. The resulting mixture was filtered through a pad of Celite[®], and the filter cake was washed with ethyl acetate (30 mL × 3). The combined filtrate was evaporated under vacuum to dryness and the residue was purified by column chromatography to yield the desired product.

Selected spectral data

2-(4-((2,2,6,6-tetramethylpiperidin-1-yl)oxy)butyl)isoindoline-1,3-dione (2n)

The general procedure was followed using (1) 0.1 mmol gram scale: 2-(4-(trifluoro-l4-boranyl)butyl)isoindoline-1,3-dione, potassium salt (1n) (30.9 mg, 0.1 mmol, 1.0 equiv.) and 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO, 1.0 equiv.) as the starting materials, alkyl-TEMPO **2n** was obtained as colorless oil (34.4 mg, yield 96%).

(2) 1.0 mmol gram scale: 2-(4-(trifluoro-l4-boranyl)butyl)isoindoline-1,3-dione, potassium salt (1n) (309.1 mg, 1.0 mmol, 1.0 equiv.) and 2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPO, 1.0 equiv.) as the starting materials, alkyl-TEMPO 2n was obtained as colorless oil (333.1 mg, yield 93%).

IR (thin film): 3500, 3080, 2980, 2840, 1888, 1680, 1620, 1550, 1470, 1220, 1010, 900, 770 cm⁻¹; ¹H NMR (400 MHz, CDCl₃) δ 7.83 (m, 2H), 7.69 (m, 2H), 3.72 (m, 2H), 1.76 (m, 2H), 1.40 (m, 4H), 1.24 (m, 4H), 1.11 (s, 6H), 1.06 (s, 6H); ¹³C NMR (100 MHz, CDCl₃) δ 168.5, 133.9, 132.1, 123.1, 75.9, 59.8, 39.6, 37.8, 32.8, 29.4, 26.2, 20.1, 16.9; HRMS (ESI⁺): Calcd for C₂₁H₃₀N₂O₃ [M+H] 375.2279, found 375.2272.

Funding

We are grateful for financial support by the National Science Foundation of China (No. 51673157) and Special Fund for Talent Research of Xijing University (Nos. XJ17B01 and XJ16T05). Thank Pro Pengfei Li (Xi'an Jiaotong University) very much for his guidance and advices during this work.

ORCID

Siyi Ding D http://orcid.org/0000-0001-5446-0254

References

- [1] (a) Renaud, P.; Sibi, M. P. *Radicals in Organic Synthesis*; Wiley-VCHL: Weinheim, 2001;
 (b) Gansäuer, A. *Radicals in Synthesis I & II*; Springer: Berlin, 2006; Vols. 263, 264;
 (c) Rowlands, G. J. *Tetrahedron* 2009 65, 8603–8655; (d) Rowlands, G. J. *Tetrahedron* 2010, 66, 1593–1636.
- [2] For selected examples for the formation of the C-C bond through radical process: (a) Ryu, I.; Sonoda, N.; Curran, D. P. Chem. Rev. 1996, 96, 177-194; (b) Wang, K. K. Chem. Rev. 1996, 96, 207-222; (c) Malacria, M. Chem. Rev. 1996, 96, 289-306; (d) Snider, B. B. Chem. Rev. 1996, 96, 339-364; (e) Gansäuer, A.; Bluhm, H. Chem. Rev. 2000, 100, 2771-2788; (f) Bar, G.; Parsons, A. F. Chem. Soc. Rev. 2003, 32, 251-283; (g) Sibi, M. P.; Manyem, S.; Zimmerman, J. Chem. Rev. 2003, 103, 3263-3296; (h) Recupero, F.; Punta, C. Chem. Rev. 2007, 107, 3800-3842; (i) Zard, S. Z. Chem. Soc. Rev. 2008, 37, 1603-1618; (j) Tang, S.; Liu, K.; Liu, C.; Lei, A. W. Chem. Soc. Rev. 2015, 44, 1070-1082.
- [3] For selected examples of the tandem radical cyclization reactions: (a) Chen, J. R.; Yu, X. Y.; Xiao, W. J. Synthesis 2014, 47, 604–629; (b) Wu, T.; Zhang, H.; Liu, G. Tetrahedron 2012, 68, 5229–5233; (c) Wei, W. T.; Zhou, M. B.; Fan, J. H.; Liu, W.; Song, R. J.; Liu, Y.; Hu, M.; Xie, P.; Li, J. H. Angew. Chem. Int. Ed. 2013, 52, 3638–3641; (d) Li, Y. M.; Sun, M.; Wang, H. L.; Tian, Q. P.; Yang, S. D. Angew. Chem. Int. Ed. 2013, 52, 3972–3976; (e) Matcha, K.; Narayan, R.; Antonchick, A. P. Angew. Chem. Int. Ed. 2013, 52, 7985–7989; (f) Shen, T.; Yuan, Y.; Jiao, N. Chem. Commun. 2014, 50, 554–556; (g) Li, Z.; Zhang, Y.; Zhang, L.; Liu, Z. Q. Org. Lett. 2014, 16, 382–385; (h) Mai, W. P.; Wang, J. T.; Yang, L. R.; Yuan, J. W.; Xiao, Y. M.; Mao, P.; Qu, L. B. Org. Lett. 2014, 16, 204–207; (i) Han, G.; Wang, Q.; Liu, Y.; Wang, Q. Org. Lett. 2014, 16, 5914–5917.
- [4] Maji, M. S.; Pfeifer, T.; Studer, A. Angew. Chem. Int. Ed. 2008, 47, 9547-9550.
- [5] Nagashima, T.; Curran, D. P. Synlett 1996, 1996, 330-332.
- [6] (a) Whitesides, G. M.; Newirth, T. L. J. Org. Chem. 1975, 40, 3448–3450; (b) Dalko, P. I. Tetrahedron Lett. 1999, 40, 4035–4036.
- [7] For selected examples of organotrifluoroborates as the coupling partners in the metal-catalyzed reactions: (a) Molander, G. A.; Figueroa, R. Aldrichim. Acta 2005, 38, 49; (b) Stefani, H. A.; Cella, R.; Vieira, A. S. Tetrahedron 2007, 63, 3623–3658; (c) Molander, G. A.; Ellis, N. Acc. Chem. Res. 2007, 40, 275–286; (d) Darses, S.; GenPt, J. P. Chem. Rev. 2008, 108, 288–325; (e) Vogler, T.; Studer, A. Synthesis 2008, 2008, 1979–1993; (f) Rudolph, A.; Lautens, M. Angew. Chem. Int. Ed. 2009, 48, 2656–2670; (g) Doucet, H. Eur. J. Org. Chem. 2010, 2008, 2013–2030; (h) Jana, R.; Pathak, T. P.; Sigman, M. S. Chem. Rev. 2011, 111, 1417–1492; (i) Kambe, N.; Iwasaki, T.; Terao, J. Chem. Soc. Rev. 2011, 40, 4937–4947; (j) Han, C.; Buchwald, S. L. J. Am. Chem. Soc. 2009, 131, 7532–7533; (k) Thaler, T.; Haag, B.; Gavryushin, A.; Schober, K.; Hartmann, E.; Gschwind, R. M.; Zipse, H.; Mayer, P.; Knochel, P. Nat. Chem. 2010, 2, 125–130; (l) Pompeo, M.; Froese, R. D. J.; Hadei, N.; Organ, M. G. Angew. Chem. Int. Ed. 2012, 51, 11354–11357; (m) Joshi-Pangu, A.; Wang, C. Y.; Biscoe, M. R. J. Am. Chem. Soc. 2011, 133, 8478–8481; (n) Bartoccini, F.; Cabri, W.; Celona, D.; Minetti, P.; Piersanti, G.; Tarzia, G. J. Org. Chem. 2010, 75, 5398–5401 (o) Molander, G. A.; Canturk, B. Angew. Chem. Int. Ed. 2009, 48, 9240–9261.
- [8] Sorin, G.; Mallorquin, R. M.; Contie, Y.; Baralle, A.; Malacria, M.; Goddard, J. P.; Fensterbank, L. Angew. Chem. Int. Ed. 2010, 49, 8721–8723.
- [9] Mn(III) complex as the oxidant for the radical formation: (a) Dickschat, A.; Studer, A. Org. Chem. 2010, 12, 3972–3974; (b) Molander, G. A.; Colombel, V.; Braz, V. A. Org. Chem. 2011, 13, 1852–1855.
- [10] Thuy-Boun, P. S.; Villa, G.; Dang, D.; Richardson, P.; Su, S.; Yu, J. Q. J. Am. Chem. Soc. 2013, 135, 17508–17513.

10 👄 S. DING ET AL.

- [11] Examples of silver nitrite as the oxidant for the radical formation: (a) Fujiwara, Y.; Domingo, V.; Seiple, I. B.; Gianatassio, R.; Bel, M. D.; Baran, P. S. J. Am. Chem. Soc. 2011, 133, 3292–3295; (b) Lockner, J. W.; Dixon, D. D.; Risgaard, R.; Baran, P. S. Org. Lett. 2011, 13, 5628–5631; (c) Liwosz, T. W.; Chemler, S. R. Org. Lett. 2013, 15, 3034–3037; (d) Presset, M.; Fleury-Brégeot, N.; Oehlrich, D.; Rombouts, F.; Molander, G. A. J. Org. Chem. 2013, 78, 4615–4619.
- [12] Examples for the single-electron transfer (SET) oxidative process which was conducted under photocatalytic conditions to form the radical: (a) Nishigaichi, Y.; Orimi, T.; Takuwa, A. J. Org. Met. Chem. 2009, 694, 3837–3839; (b) Yasu, Y.; Koike, T.; Akita, M. Adv. Synth. Catal. 2012, 354, 3414–3420; (c) Huang, H.; Zhang, G.; Gong, L.; Zhang, S.; Chen, Y. J. Am. Chem. Soc. 2014, 136, 2280–2283; (d) Tellis, J. C.; Primer, D. N.; Molander, G. A. Science 2014, 345, 433–436; (e) Gutierrez, O.; Tellis, J. C.; Primer, D. N.; Molander, G. A.; Kozlowski, M. C. J. Am. Chem. Soc. 2015, 137, 4896–4899; (f) Oderinde, M. S.; Varela-Alvarez, A.; Aquila, B.; Robbins, D. W.; Johannes, J. W. J. Org. Chem. 2015, 80, 7642–7651; (g) Primer, D. N.; Karakaya, I.; Tellis, J. C.; Molander, G. A. J. Am. Chem. Soc. 2015, 137, 2195–2198; (h) Dai, J.; Zhang, W.; Shu, Y.; Sun, Y.; Xu, J.; Feng, Y.; Xu, H. Chem. Commun. 2016, 52, 6793–6796; (i) Nishigaichi, Y.; Orimi, T.; Koyachi, K.; Ohmuro, Y.; Suzuki, M. Chem. Lett. 2016, 45, 1382–1384; (j) Chen-Neberg, L.; Lévêque, C.; Corcé, V.; Fensterbank, L. Synlett 2016, 27, 731–735; (k) Zhang, W.; Dai, J.; Xu, J.; Xu, H. J. Org. Chem. 2017, 82, 2059–2066.
- [13] Ding, S. Y.; Xu, L.; Li, P. F. ACS Catal. 2016, 6, 1329-1333.
- [14] For selected examples for the radical cyclization reaction to form the substituted phenanthridine derivatives: (a) Zhang, B.; Muck-Lichtenfeld, C.; Daniliuc, C. G.; Studer, A. Angew. Chem. Int. Ed. 2013, 52, 10792–10795; (b) Jiang, H.; Cheng, Y.; Wang, R.; Zheng, M.; Zhang, Y.; Yu, S. Angew. Chem. Int. Ed. 2013, 52, 13289–13292; (c) Liu, J.; Fan, C.; Yin, H.; Qin, C.; Zhang, G.; Zhang, X.; Lei, A. W. Chem. Commun. 2014, 50, 2145–2147; (d) Xu, Z.; Yan, C.; Liu, Z. Org. Lett. 2014, 16, 5670–5673; (e) Zhang, B.; Studer, A. Org. Lett. 2014, 16, 3990–3993; (f) Fang, H.; Zhao, J.; Ni, S.; Mei, H.; Han, J.; Pan, Y. J. Org. Chem. 2015, 80, 3151–3158; (g) Zhou, Y.; Wu, C.; Dong, X.; Qu, J. J. Org. Chem. 2016, 81, 5202–5208; (h) Yao, Q.; Zhou, X.; Zhang, X.; Wang, C.; Wang, P.; Li, M. Org. Biomol. Chem. 2017, 15, 957–971.