



Cite this: *Chem. Commun.*, 2019, 55, 4039

Received 8th February 2019,
Accepted 6th March 2019

DOI: 10.1039/c9cc01146c

rsc.li/chemcomm

Synthesis of indoles and quinazolines *via* additive-controlled selective C–H activation/annulation of *N*-arylamidines and sulfoxonium ylides†

Ruizhi Lai, Xiaohua Wu, Songyang Lv, Chen Zhang, Maoyao He, Yuncan Chen, Qiantao Wang, Li Hai * and Yong Wu *

Selective synthesis of indole and quinazoline products was achieved through a precise control of the C–H activation/annulation by changing the additives from NaOAc to CuF₂/CsOAc. This strategy constructs indole and quinazoline scaffolds efficiently, and hence is of great interest in pharmaceutical, agricultural and chemical industries.

Transition-metal-catalyzed C–H activation has been extensively explored as it usually avoids the multistep preactivation of the starting materials providing an atom- and step-economical strategy for organic synthesis.¹ For instance, C–H activation/annulation, which has been one of the hottest topics in recent years,² does not only specifically functionalize the inert C–H bonds, but also forms a variety of cyclic compounds by coupling and cyclization with the introduced functional groups.

Indoles and quinazolines are two well-known classes of nitrogen-containing heterocyclic compounds that pose a broad-spectrum of biological activities and have been widely used in pharmaceutical, agricultural and chemical industries (Fig. 1).³ Therefore, a more economical and environment-friendly synthetic strategy would be of great interest in the field. Among the published works, the formation of indoles was achieved mainly through the C–H activation

of aniline derivatives with coupling reagents, such as alkene, alkyne and diazo (Scheme 1a).⁴ On the other hand, quinazolines were mainly afforded *via* the C–H activation of benzimidates with amino reagents (dioxazolones and alkyl azides) or by the reactions of *N*-arylamidines with the “one-carbon coupling reagents” (C1 unit) like isonitrile and alkyne derivatives (Scheme 1b).⁵

Although the synthesis of indoles and quinazolines has been widely studied, most of the methods still have some drawbacks, such as the use of toxic and dangerous reagents (isonitrile, diazo, azide, *etc.*) and the unsatisfactory yields. Recently, sulfoxonium ylides have been widely used as a convenient and safe carbene precursor reagent in transition-metal-catalyzed C–H

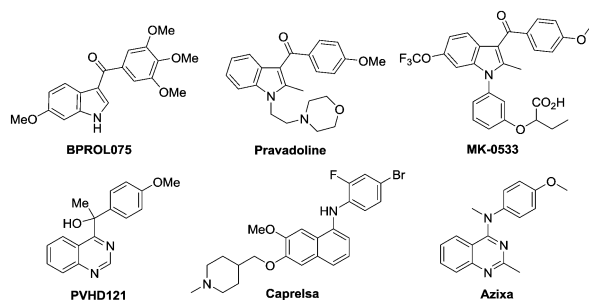


Fig. 1 Selected examples of bioactive indoles and quinazolines.

Key Laboratory of Drug-Targeting of Education Ministry and Department of Medicinal Chemistry, West China School of Pharmacy, Sichuan University, Chengdu 610041, China. E-mail: wyong@scu.edu.cn, smile@scu.edu.cn

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c9cc01146c



Scheme 1 C–H activation/annulation for the synthesis of indoles and quinazolines.

activation/annulation.⁶ Many groups independently reported C–H activation/annulation cascade reactions of different directing groups (DGs) with sulfoxonium ylides as the C2 unit to obtain lactones, lactams, isoquinolines, azolopyrimidines, naphthols, *etc.*^{6a–i} In addition, Kim's group recently used azobenzene with sulfoxonium ylide as the C1 unit to synthesize indazoles.^{6j} Collectively, these results revealed that sulfoxonium ylide played an important role in C–H activation/annulation. As our group has been interested in C–H activation in recent years,⁷ we were wondering whether it is possible to use *N*-arylamidines and sulfoxonium ylides to synthesize *N*-heterocycles through C–H activation/annulation. Herein, to answer this question, we report our most recent work on additive-controlled selective synthesis of indoles and quinazolines by using *N*-arylamidines and sulfoxonium ylides as the starting materials (Scheme 1c).

Initially, we selected *N*-phenylacetimidamide **1a** as a substrate to react with dimethyloxosulfonium benzoylmethylide **2a** using [Cp*RhCl₂]₂ (5 mol%)/AgSbF₆ (20 mol%) as the catalyst. To our delight, (2-methyl-1*H*-indol-3-yl)(phenyl)methanone **3a** and 2-methyl-4-benzoylquinazoline **5a** were obtained in a 1 : 1 ratio with 62% total yield (Table 1, entry 1). Then, the relationship between additives and reaction results was explored (entries 2–11). It was shown that NaOAc as a base was obviously favored to generate the indole product **3a** (entry 3), while Cu salt, especially CuF₂, afforded quinazoline product **5a** mostly (entry 11). The effect of the solvent was also examined, and it turned out that DCE was the best (see the ESI†). Increasing the reaction temperature would cause serious side-reactions of

ylide hence lowering the yield (see the ESI†). Increasing the amount of **2a** only improved the yield of **3a** (entries 12 and 13), and the formation of **5a** was favored by the oxygen environment (entry 14). In addition, as we found that CsOAc had a mild preference on **5a** (entry 5), we combined it with CuF₂ to see if it can further boost the yield. Fortunately, **5a** was obtained in 74% yield (entry 15).

With the optimized reaction conditions in hand, the C–H activation of imidamides was examined. Firstly, the substrate generality of indole products was explored, and the results are shown in Table 2. Unsubstituted *N*-phenylacetimidamide afforded **3a** with 78% isolated yield. The electron-donating, electron-withdrawing and halogen groups introduced into different positions of the benzene ring were fully tolerated (**3b–3q**), giving good to excellent yields (60–85%) for the indole products. Notably, when isopropyl, isobutyl, methoxyethyl and benzyl groups were introduced into *C*-alkyl imidamides, the reaction also successfully afforded desired products (**3r–3u**). Given the above results, it was found that the electron-donating groups, such as Me and OMe, and halogens on the phenyl were more favorable for this transformation than the electron-withdrawing groups including CF₃, nitro, acetyl and ester (**3g–3j**). In addition, the different substituting positions of the benzene ring affected the yields as well. The *para*-substitution was slightly better than the *meta*-, and the *meta*- was better than the *ortho*-. It was also found that when the imidamide was *meta*-monosubstituted by Me, both **3k** and **3'k** were produced in a ratio of 5 : 1. However, when Me was changed to F or Cl, only one regioisomer could be obtained (**3l** and **3m**). The difference in regioisomer formation may be the result of a combination of the steric effects and the electrical effects. Then, the change of sulfoxonium ylides was also investigated. When Me, MeO and halogen groups were attached to different positions on the benzene ring of sulfoxonium ylides, the reactions were fully tolerated (**4a–4i**), furnishing the desired products in good to excellent

Table 1 Optimization of the reaction conditions^a

			Yield ^b (%)	
Entry	Additive		3a	5a
1	—		33	29
2	HOAc		28	31
3	NaOAc		62	10
4	AgOAc		58	10
5	CsOAc		21	43
6	CsCO ₃		27	35
7	Cu(OAc) ₂		< 5	51
8	Cu(TFA) ₂		< 5	42
9	Cu(OTf) ₂		< 5	45
10	CuCl ₂		< 5	31
11	CuF ₂		< 5	54
12 ^c	NaOAc		78	< 5
13 ^c	CuF ₂		< 5	52
14 ^d	CuF ₂		< 5	68
15 ^{d,e}	CuF ₂ /CsOAc		< 5	74

^a Unless otherwise noted, all the reactions were carried out using *N*-phenylacetimidamide **1a** (0.20 mmol) and dimethyloxosulfonium benzoylmethylide **2a** (0.40 mmol) in the presence of [Cp*RhCl₂]₂ (0.01 mmol), AgSbF₆ (0.04 mmol), additive (0.40 mmol) and DCE (1.0 ml) in a Schlenk tube, and the mixture was stirred at 80 °C for 24 h under Ar.

^b Isolated yield by chromatography on a silica gel. ^c Dimethyloxosulfonium benzoylmethylide **2a** = 0.60 mmol. ^d O₂ atmosphere. ^e CsOAc = 0.20 mmol.

Table 2 Synthesis of indoles^a

			Yield ^b (%)	
Entry	Additive		3a	5a
1	—		78	< 5
2	HOAc		74	31
3	NaOAc		62	10
4	AgOAc		58	10
5	CsOAc		21	43
6	CsCO ₃		27	35
7	Cu(OAc) ₂		< 5	51
8	Cu(TFA) ₂		< 5	42
9	Cu(OTf) ₂		< 5	45
10	CuCl ₂		< 5	31
11	CuF ₂		< 5	54
12 ^c	NaOAc		78	< 5
13 ^c	CuF ₂		< 5	52
14 ^d	CuF ₂		< 5	68
15 ^{d,e}	CuF ₂ /CsOAc		< 5	74

^a Reaction conditions: *N*-arylethanimidamides **1** (0.20 mmol), dimethyloxosulfonium benzoylmethylide **2a** (0.60 mmol), [Cp*RhCl₂]₂ (0.01 mmol), AgSbF₆ (0.04 mmol), NaOAc (0.40 mmol) and DCE (1.0 ml) in a Schlenk tube. The mixture was stirred at 80 °C for 24 h under Ar. Then, without any post processing, the reaction mixture was purified by column chromatography on a silica gel (eluent: PE/DCM = 1/1) to afford the desired product.

yields (66–82%). Notably, sulfoxonium ylides with MeO *ortho*-bisubstitution on the benzene ring had a yield of 66% only (**4i**). This may be due to the greatly increasing steric hindrance. When the benzene ring of ylide was changed to a naphthalene ring or a 1,3-benzodioxole ring, the reaction still proceeded smoothly and gave good yields (**4j** and **4k**). Once the benzene ring of the ylide was changed to Me (**2l**) or *t*-Bu (**2m**), no product was formed. It seemed that the aromaticity of the sulfoxonium ylide could be necessary in this reaction.

Then, we turned our attention to the synthesis of quinazolines (Table 3). Unsubstituted *N*-phenylacetimidamide gave 74% isolated yield of **5a**. The electron-donating, electron-withdrawing and halogen groups introduced into different positions of the benzene ring were fully tolerated (**5a–5p**), and the extension of the terminal carbon chain seemed to have no effect on the reaction (**5q** and **5r**), giving moderate to excellent yields (54–85%). Notably, when the benzene ring was *meta*-monosubstituted with Me, C–H activation took place in the C(6) site producing **5p**. However, when Me was changed to F or Cl, C–H activation took place in the C(2) site producing **5l** or **5m**. The results above may be the interaction of the steric effects and the electrical effects. Then, sulfoxonium ylides were investigated to further explore the substrate generality of quinazoline products. When Me, MeO and halogen groups were attached to different positions on the benzene ring of sulfoxonium ylides, the reactions were fully tolerated (**6a–6g**), furnishing the desired products in good yields (67–78%). Similarly, once the benzene ring of the ylide was changed to Me (**2l**) or *t*-Bu (**2m**), no product was found.

To gain mechanistic insight into the reaction, a series of experiments have been conducted (see the ESI†).⁸ Based on the above results and previous related studies,^{6g,9} a possible mechanism for this protocol is shown in Scheme 2. Cyclometalation of *N*-phenylacetimidamide **1a** and the active Rh(III) catalyst gives a rhodacyclic intermediate **A**. Coordination of dimethyloxosulfonium

benzoylmethylide **2a** generates a Rh(III) alkyl species **B**, and the subsequent α -elimination of DMSO from **B** affords a reactive rhodium α -oxo carbene species **C**. Following the formation of **C**, two pathways may be possible. In pathway A, **C** is proposed to undergo migratory insertion of the Rh–C bond to generate a seven-membered rhodacyclic intermediate **D**. Intermediate **E** is then formed from unstable intermediate **D** by Rh–C(alkyl) migratory insertion into the C–N bond. Eventually, the final product **3a** is released from **E** by elimination of the active Rh(III) catalyst and one molecule of ammonia from **E** upon protonolysis and intramolecular protonolysis. In pathway B, the seven-membered rhodacyclic intermediate **D** is still generated. Then, the reductive elimination from intermediate **D** forms partially reduced quinazoline **F**. Subsequently, the oxidation of **F** affords the quinazoline product **5a**. On the other hand, the resulting Cp*Rh(I) can be reoxidized to the starting Rh(III) species by the action of Cu(II) and/or O₂ to complete the catalytic cycle.

It is noteworthy that this protocol really has many practical applications. For example, Pravadinolone, a phase II drug, was recognized as a cannabinoid CB1 receptor agonist and has a strong analgesic effect (IC₅₀ = 4.9 μ M).¹⁰ *N*-methylacetimidamide **1a** and dimethyloxosulfonium 4-methoxybenzoylmethylide **2c** were used to synthesize Pravadinolone **9** in a shorter route yet with a higher yield, *i.e.* a total yield of 70%, in two steps (Scheme 3a). On the other hand, indole and quinazoline scaffolds have a broad-spectrum of biological activities. Based on a previous work,¹¹ we synthesized several indole compounds using our protocol (Scheme 3b), and we also choose several quinazoline compounds we synthesized (Scheme 3c). The anti-tumor activity of these indole and quinazoline compounds was evaluated. 3-Aroylindoles (**11a–11d**) all had excellent anti-tumor activity, while quinazoline products (**5n**, **5o**, **5q**, **5r**) put up a poor show. In comparison with BPR-0L-075, compounds **11b**, **11c** and **11d** displayed similar or greater growth inhibitory activities (see the ESI†).

Table 3 Synthesis of quinazolines^a

1	2	Condition B	5-6
		$[\text{Cp}^*\text{RhCl}_2]_2$ / 5 mol% AgSbF ₆ / 20 mol%; CuF ₂ / 2.0 eq CsOAc / 1.0 eq; DCE, O ₂ , 80 °C, 24 h	
R = H, 5a , 74%	R = Me, 5b , 74%	R = OMe, 5c , 78%	R = F, 5d , 80%
R = Cl, 5e , 78%	R = Br, 5f , 77%	R = CF ₃ , 5g , 62%	R = COMe, 5h , 54%
R = <i>n</i> -Pr, 5q , 80%	R = (CH ₂) ₂ OMe, 5r , 75%		
R = 4-Me, 6a , 75%	R = 4-Cl, 6b , 78%	R = 3,5-di-Me, 6c , 71%	R = 3-OMe, 6d , 77%
R = 3-Cl, 6e , 74%	R = 2-Me, 6f , 67%	R = 2-Cl, 6g , 68%	
R ₃ = Me, 2l	R ₃ = <i>t</i> -Bu, 2m	No reaction	

^a Reaction conditions: *N*-arylethanimidamides **1** (0.20 mmol), dimethyloxosulfonium benzoylmethylide **2a** or **2c** (0.40 mmol), [Cp*RhCl₂]₂ (0.01 mmol), AgSbF₆ (0.04 mmol), CuF₂ (0.40 mmol), CsOAc (0.20 mmol) and DCE (1.0 ml) in a Schlenk tube. The mixture was stirred at 80 °C for 24 h under O₂. Then, without any post processing, the reaction mixture was purified by column chromatography on a silica gel (eluent: PE/acetone = 50/1) to afford the desired product.



Scheme 2 Possible pathways of the C–H activation/cyclization.



Scheme 3 The practical applications of this protocol.

It is worth pinpointing that our highly efficient and scalable methodology for the synthesis of 3-arylindoles and 4-arylquinazolines will be extremely useful in discovering the novel anti-tumor compounds, and it may provide new ideas for drug design and synthesis.

In summary, we report the first example, to the best of our knowledge, of an additive-controlled selective C–H activation/annulation reaction of *N*-arylamidines and sulfoxonium ylides to selectively synthesize indoles and quinazolines. In this process, the additives were shown to play a key role in selectively controlling the [4+1] and [5+1] annulation. With the additive NaOAc, the reaction predominantly gave the indoles because of the [4+1] annulation. Changing the additives to CuF₂/CsOAc, the preference of the annulation was switched to [5+1], hence selectively affording the quinazoline products. Furthermore, this simple, rapid and efficient strategy may provide a new tool for the synthesis of N-heterocycles, hence facilitating chemical synthesis and drug design.

Financial support from the National Natural Science Foundation of China (NSFC; grant numbers 81573286, 81773577 and 81602954) and the Fundamental Research Funds for the Central Universities (YJ201561) is gratefully acknowledged.

Conflicts of interest

There are no conflicts to declare.

Notes and references

- 1 Selected reviews for C–H activation: (a) D. A. Colby, R. G. Bergman and J. A. Ellman, *Chem. Rev.*, 2010, **110**, 624; (b) N. Kuhl, N. Schröder

and F. Glorius, *Adv. Synth. Catal.*, 2014, **356**, 1443; (c) X.-S. Zhang, K. Chen and Z.-J. Shi, *Chem. Sci.*, 2014, **5**, 2146; (d) P. L. Arnold, M. W. McMullon, J. Rieb and F. E. Kühn, *Angew. Chem., Int. Ed.*, 2015, **54**, 82; (e) F. Wang, S. Yu and X. Li, *Chem. Soc. Rev.*, 2016, **45**, 6462.

- 2 Selected reviews for C–H activation/annulation: (a) T. Satoh and M. Miura, *Chem. – Eur. J.*, 2010, **16**, 11212; (b) G. Song, F. Wang and X. Li, *Chem. Soc. Rev.*, 2012, **41**, 3651.
- 3 (a) M. Somei and F. Yamada, *Nat. Prod. Rep.*, 2004, **21**, 278; (b) A. J. Kochanowska-Karamyan and M. T. Hamann, *Chem. Rev.*, 2010, **110**, 4489; (c) G. Marzaro, A. Guiotto and A. Chilin, *Expert Opin. Ther. Pat.*, 2012, **22**, 223.
- 4 Selected examples: (a) J. Chen, G. Song, C. Pan and X. Li, *Org. Lett.*, 2010, **12**, 5426; (b) M. P. Huestis, L. R. Chan, D. R. Stuart and K. Fagnou, *Angew. Chem., Int. Ed.*, 2011, **50**, 1338; (c) C. Wang, H. Sun, Y. Fang and Y. Huang, *Angew. Chem., Int. Ed.*, 2013, **52**, 5795; (d) Y. Liang, K. Yu, B. Li, S. Xu, H. Song and B. Wang, *Chem. Commun.*, 2014, **50**, 6130; (e) D. Zhao, S. Vasquez-Céspedes and F. Glorius, *Angew. Chem., Int. Ed.*, 2015, **54**, 1657; (f) Z. Qi, S. Yu and X. Li, *Org. Lett.*, 2016, **18**, 700; (g) K. S. Halskov, H. S. Roth and J. A. Ellman, *Angew. Chem., Int. Ed.*, 2017, **56**, 9183; (h) F. Xu, W.-F. Kang, Y. Wang, C.-S. Liu, J.-Y. Tian, R.-R. Zhao and M. Du, *Org. Lett.*, 2018, **20**, 3245; (i) J. Zhou, J. Li, Y. Li, C. Wu, G. He, Q. Yang, Y. Zhou and H. Liu, *Org. Lett.*, 2018, **20**, 7645.
- 5 Selected examples: (a) Y. Wang, H. Wang, J. Peng and Q. Zhu, *Org. Lett.*, 2011, **13**, 4604; (b) H. Wang, M. M. Lorian and L. Ackermann, *Angew. Chem., Int. Ed.*, 2016, **55**, 10386; (c) F. Wang, H. Wang, Q. Wang, S. Yu and X. Li, *Org. Lett.*, 2016, **18**, 1306; (d) X. Wang and N. Jiao, *Org. Lett.*, 2016, **18**, 2150; (e) F. Xu, W.-F. Kang, Y. Wang, C.-S. Liu, J.-Y. Tian, R.-R. Zhao and M. Du, *Org. Lett.*, 2018, **20**, 3245.
- 6 (a) A. M. Phelps, V. S. Chan, J. G. Napolitano, S. W. Krabbe, J. M. Schomaker and S. Shekhar, *J. Org. Chem.*, 2016, **81**, 4158; (b) J. Vaitla, A. Bayer and K. H. Hopmann, *Angew. Chem., Int. Ed.*, 2017, **56**, 4277; (c) Y. Xu, G. Zheng, X. Yang and X. Li, *Chem. Commun.*, 2018, **54**, 670; (d) X. Wu, H. Xiong, S. Sun and J. Cheng, *Org. Lett.*, 2018, **20**, 1396; (e) K. S. Halskov, M. R. Witten, G. L. Hoang, B. Q. Mercado and J. A. Ellman, *Org. Lett.*, 2018, **20**, 2464; (f) G. L. Hoang and J. A. Ellman, *Tetrahedron*, 2018, **74**, 3318; (g) G. Zheng, M. Tian, Y. Xu, X. Chen and X. Li, *Org. Chem. Front.*, 2018, **5**, 998; (h) C. Zhou, F. Fang, Y. Cheng, Y. Li, H. Liu and Y. Zhou, *Adv. Synth. Catal.*, 2018, **360**, 2546; (i) C.-F. Liu, M. Liu and L. Dong, *J. Org. Chem.*, 2019, **84**, 409; (j) H. Oh, S. Han, A. K. Pandey, S. H. Han, N. K. Mishra, S. Kim, R. Chun, H. S. Kim, J. Park and I. S. Kim, *J. Org. Chem.*, 2018, **83**, 4070.
- 7 C. Zhang, X.-M. Chen, Y. Luo, J.-L. Li, M. Chen, L. Hai and Y. Wu, *ACS Sustainable Chem. Eng.*, 2018, **6**, 13473.
- 8 (a) E. M. Simmons and J. F. Hartwig, *Angew. Chem., Int. Ed.*, 2012, **51**, 3066; (b) M. Tian, B. Liu, J. Sun and X. Li, *Org. Lett.*, 2018, **20**, 4946.
- 9 (a) M. Brasse, J. Cámpora, J. A. Ellman and R. G. Bergman, *J. Am. Chem. Soc.*, 2013, **135**, 6427; (b) X. Zhou, Z. Qi, S. Yu, L. Kong, Y. Li, W. Tian and X. Li, *Adv. Synth. Catal.*, 2017, **359**, 1620; (c) Y. Xu, G. Zheng, X. Yang and X. Li, *Chem. Commun.*, 2018, **54**, 670; (d) B. Alcaide, P. Almendros, I. Fernández, T. M. D. Campo and T. Naranjo, *Adv. Synth. Catal.*, 2013, **355**, 2681; (e) J. Schiefl, J. Schulmeister, A. Doppiu, E. Wörner, M. Rudolph, R. Karch and A. S. K. Hashmi, *Adv. Synth. Catal.*, 2018, **360**, 3949.
- 10 J. M. Frost, M. J. Dart, K. R. Tietje, T. R. Garrison, G. K. Grayson, A. V. Daza, O. F. El-Kouhen, B. B. Yao, G. C. Hsieh, M. Pai, C. Z. Zhu, P. Chandran and M. D. Meyer, *J. Med. Chem.*, 2010, **53**, 295.
- 11 (a) J.-P. Liou, Y.-L. Chang, F.-M. Kuo, C.-W. Chang, H.-Y. Tseng, C.-C. Wang, Y.-N. Yang, J.-Y. Chang, S.-J. Lee and H.-P. Hsieh, *J. Med. Chem.*, 2004, **47**, 4247; (b) M. A. Soussi, O. Provot, G. Bernadat, J. Bignon, D. Desravines, J. Dubois, J.-D. Brion, S. Messaoudi and M. Alami, *ChemMedChem*, 2015, **10**, 1392; (c) K. Kuroiwa, H. Ishii, K. Matsuno, A. Asai and Y. Suzuki, *ACS Med. Chem. Lett.*, 2015, **6**, 287.