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# *In situ* generated CF<sub>3</sub>CHN<sub>2</sub> with 3-ylideneoxindoles to access CF<sub>3</sub>-containing pyrazolo[1,5-*c*]quinazolines derivatives†

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Toward a selective and facile method for the synthesis of CF<sub>3</sub>-containing pyrazolo[1,5-*c*]quinazolines, we developed a [3 + 2] cycloaddition/1,3-H shift/rearrangement/dehydrogenation cascade involving *in situ* generated CF<sub>3</sub>CHN<sub>2</sub> and 3-ylideneoxindoles with DBU as a base. The reaction is distinguished by its mild conditions, metal-free process, operational simplicity, and broad functional group tolerance, thus presenting a convenient protocol for the construction of pyrazolo[1,5-*c*]quinazolines that are of interest in medicinal chemistry.

## Introduction

The trifluoromethyl group, which can be regarded as a classical group in drugs and drug candidates, was introduced to modulate physicochemical properties and increase the binding affinity of molecules. For instance, the drugs Prozac, Celebrex and Januvia are all active agents.<sup>1</sup> Therefore, the introduction of the trifluoromethyl group is of great interest in various areas of organic and medicinal chemistry.<sup>2</sup> In particular, direct trifluoromethylation plays a pivotal part in organic chemistry. Numerous methods have been demonstrated to be able to promote C(sp<sup>2</sup>)-CF<sub>3</sub> bond formation, including nucleophilic trifluoromethylation,<sup>3</sup> electrophilic trifluoromethylation,<sup>4</sup> and radical trifluoromethylation.<sup>5</sup> In recent years, radical trifluoromethylation has been explored as a powerful tool for the construction of the C(sp<sup>2</sup>)-CF<sub>3</sub> bond.<sup>6</sup> Trifluoromethyl free radicals serve as active species in radical trifluoromethylation.<sup>7</sup>

Alternatively, other routes based on the chemical conversions of CF<sub>3</sub>-containing building blocks,<sup>8</sup> especially trifluorodiazaoethane (CF<sub>3</sub>CHN<sub>2</sub>),<sup>9</sup> have emerged as a valuable reagent for introducing trifluoromethyl groups into heterocyclic compounds. CF<sub>3</sub>CHN<sub>2</sub> readily participates in [2 + 1]-, [3 + 2]-, and [3 + 3]-cycloaddition reactions as a trifluoromethyl-containing dipole, thereby creating new approaches to synthesize CF<sub>3</sub>-containing heterocycles.<sup>10</sup> This impressive work

stemmed from a study by the group of Xiao and Lu,<sup>11</sup> who reported a [3 + 2] cycloaddition/ring contraction sequence of 3-ylideneoxindoles with *in situ* generated CF<sub>3</sub>CHN<sub>2</sub> without a transition-metal catalyst. Initial [3 + 2] cycloaddition occurred smoothly to give corresponding cycloadducts, and the subsequent ring contraction reaction worked very well in refluxing PhMe to afford the final CF<sub>3</sub>-substituted 3,3'-cyclopropyl spirooxindoles.

Owing to the significant biological activities of both quinazoline and pyrazole derivatives, pyrazolo[1,5-*c*]quinazolines formed by *N*-fusing quinazolines with pyrazoles have occupied an important position in drug design. Examples of the biological activities of pyrazolo[1,5-*c*]quinazolines include Gly/NMDA antagonists,<sup>12</sup> phosphodiesterase 10A inhibitors,<sup>13</sup> benzodiazepine/adenosine receptors,<sup>14</sup> and AMPA receptors (Fig. 1).<sup>15</sup> Accordingly, considerable efforts have been undertaken to develop efficient synthetic strategies for these

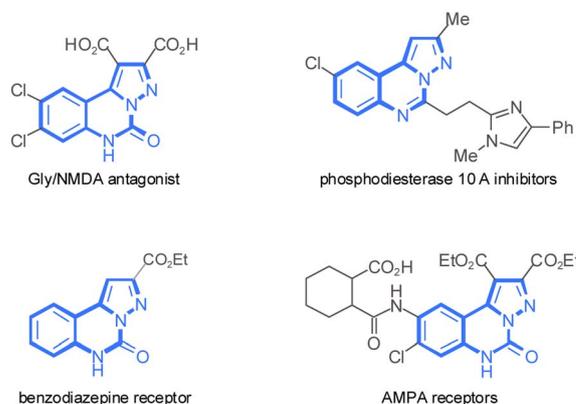


Fig. 1 Some biologically active compounds with a pyrazolo[1,5-*c*]quinazoline core.

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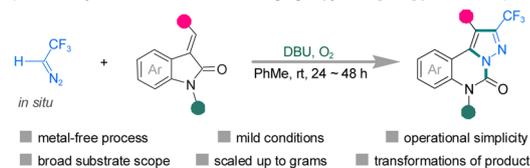
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A) Visible-light-induced [3 + 2] cycloaddition for construction of 1,3,4-oxadiazoles<sup>17</sup>B) Rh-catalyzed [2 + 1 + 2] cycloadditions for synthesis of imidazo[1,5-a] N-heterocycles<sup>18</sup>

C) DBU-catalyzed cascade reaction for forging of pyrazolo[1,5-c]quinazolines (this work)



Scheme 1 Applications of *in situ* generated  $\text{CF}_3\text{CHN}_2$  in the construction of  $\text{CF}_3$ -containing N-heterocycles.

fascinating bioactive molecules.<sup>16</sup> However, some involved multistep synthesis, harsh reaction conditions, lower yields, or poor chemoselectivity. Therefore, the development of readily available and easily accessible pyrazolo[1,5-*c*]quinazolines is exciting and practically useful.

In 2021, we reported a visible-light-induced [3 + 2] cycloaddition of  $\alpha$ -ketoacids with a hypervalent iodine(III) reagent derived from *in situ* generated  $\text{CF}_3\text{CHN}_2$  for the synthesis of 5- $\text{CF}_3$ -1,3,4-oxadiazoles (Scheme 1A).<sup>17</sup> Recently, a novel sulfonium salt derived from *in situ* generated  $\text{CF}_3\text{CHN}_2$  was prepared by our group, and it was applied in Rh-catalyzed [2 + 1 + 2] cycloadditions to afford imidazo[1,5-*a*] N-heterocycles (Scheme 1B).<sup>18</sup> As part of our continuing interests in organic fluorine chemistry,<sup>19</sup> as well as our recent progress in cycloadditions for the synthesis of N-heterocycles from *in situ* generated  $\text{CF}_3\text{CHN}_2$  and its derivatives,<sup>17–19</sup> we further applied a [3 + 2] cycloaddition/1,3-H shift/rearrangement/dehydrogenation cascade process starting from easily available 3-ylideneoxindoles and  $\text{CF}_3\text{CHN}_2$  to efficiently form pyrazolo[1,5-*c*]quinazoline containing a  $\text{CF}_3$  group. Herein, we wish to report our preliminary studies on this subject (Scheme 1C).

## Results and discussion

We commenced our investigation by screening reaction parameters for the coupling between *in situ* generated  $\text{CF}_3\text{CHN}_2$  (2) and 3-ylideneoxindole 3a (Table 1). Using DBU as a base, a coupling occurred, and the desired  $\text{CF}_3$ -containing pyrazolo[1,5-*c*]quinazoline product 4a was isolated in 40% yield in the presence of  $\text{Et}_2\text{O}$  (Table 1, entry 1). Switching the solvent to DCM slightly decreased the yield (Table 1, entry 4). Different solvents were also investigated; however, this led to no desired reaction (Table 1, entries 2 and 3). The reaction time is significantly prolonged when utilizing alternative solvents, such as  $\text{Et}_2\text{O}$  and DCM, which require a duration of 120 h. Interestingly, employing PhMe as the reaction solvent enables the completion of the entire reaction within a span of 48 h. PhMe was found to

Table 1 Investigation of reaction conditions<sup>a</sup>

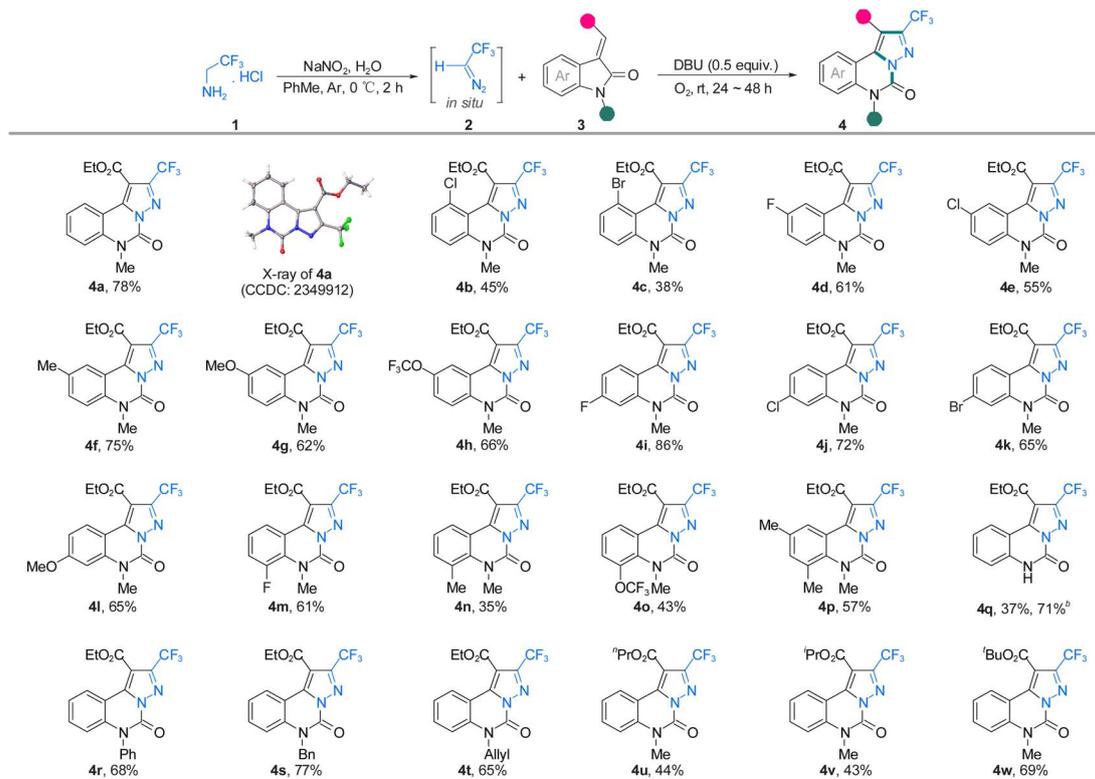
Entry	Solvent	Temperature	Base (x equiv.)	Yield <sup>b</sup> (%)
1 <sup>c</sup>	$\text{Et}_2\text{O}$	r.t.	DBU (0.5)	40
2 <sup>c</sup>	1,4-Dioxane	r.t.	DBU (0.5)	N.R.
3 <sup>c</sup>	THF	r.t.	DBU (0.5)	N.R.
4 <sup>c</sup>	DCM	r.t.	DBU (0.5)	33
5	PhMe	r.t.	DBU (0.5)	78
6 <sup>d</sup>	PhMe	r.t.	DBU (0.5)	39
7 <sup>e</sup>	PhMe	r.t.	DBU (0.5)	55
8 <sup>f</sup>	PhMe	r.t.	DBU (0.5)	68
9	PhMe	r.t.	$\text{CS}_2\text{CO}_3$ (0.5)	N.R.
10	PhMe	r.t.	$\text{K}_2\text{CO}_3$ (0.5)	N.R.
11	PhMe	r.t.	$\text{Et}_3\text{N}$ (0.5)	N.R.
12	PhMe	r.t.	NaOH (0.5)	N.R.
13	PhMe	r.t.	<sup>t</sup> BuOK (0.5)	N.R.
14	PhMe	r.t.	DBN (0.5)	50
15	PhMe	r.t.	DBU (0.25)	60
16	PhMe	r.t.	DBU (0.75)	60
17	PhMe	r.t.	DBU (1.0)	50
18	PhMe	$-10\text{ }^\circ\text{C}$	DBU (0.5)	66
19	PhMe	$0\text{ }^\circ\text{C}$	DBU (0.5)	59
20	PhMe	$40\text{ }^\circ\text{C}$	DBU (0.5)	46

<sup>a</sup> Standard conditions: performed with  $\text{CF}_3\text{CH}_2\text{NH}_2 \cdot \text{HCl}$  (1.5 mmol, 6.0 equiv.),  $\text{NaNO}_2$  (1.65 mmol, 6.6 equiv.) 0.2 mL  $\text{H}_2\text{O}$  at  $0\text{ }^\circ\text{C}$  for 2 h. The mixture was dried, and later 3a (0.25 mmol, 1.0 equiv.), DBU (0.5 equiv.) and 5 mL of drying solvent were added at room temperature under an  $\text{O}_2$  atmosphere (balloon) for 48 h. <sup>b</sup> Isolated yields based on 3a are given. <sup>c</sup> The reaction was performed for 120 h. <sup>d</sup> The reaction was performed in 3 mL of dry solvent. <sup>e</sup> The reaction was performed in 10 mL dry solvent. <sup>f</sup> The reaction was performed in 15 mL dry solvent.

be superior to the others, and product 4a was obtained in 78% yield within the optimal reaction time (48 h) (Table 1, entry 5). We also screened the bases required for the reaction and found that  $\text{CS}_2\text{CO}_3$ ,  $\text{K}_2\text{CO}_3$ ,  $\text{Et}_3\text{N}$ , NaOH, and <sup>t</sup>BuOK (Table 1, entries 9–13) could not perform the expected reaction. Only DBN provides the required product 4a in 50% yield (Table 1, entry 14). Screening with base loading showed that 0.5 equiv. was better than other methods, with a yield of 78% (Table 1, entries 15–17 vs. entry 5). The effect of temperature was also examined, and all resulted in slightly reduced yields, and room temperature was confirmed to be the best one (Table 1, entries 18–20 vs. entry 5). Therefore, the optimal reaction conditions were summarized:  $\text{CF}_3\text{CH}_2\text{NH}_2 \cdot \text{HCl}$  (203.25 mg, 1.5 mmol, 6.0 equiv.),  $\text{NaNO}_2$  (115.5 mg, 1.65 mmol, 6.6 equiv.) and  $\text{H}_2\text{O}$  (0.2 mL) were stirred in 5.0 mL of PhMe at  $0\text{ }^\circ\text{C}$  for 2 h in a 100 mL double-necking bottle under Ar. After drying  $\text{Na}_2\text{SO}_4$ , 3a (57.6 mg, 0.25 mmol, 1.0 equiv.) and DBU (0.5 equiv.) were added, and the reaction mixture was stirred at room temperature under an  $\text{O}_2$  atmosphere (balloon) for 48 h.

With the optimized reaction conditions in hand, the scope and generality concerning  $\text{CF}_3\text{CHN}_2$  were next examined in the coupling of compound 4 (Scheme 2). The introduction of fluorine, chlorine, and bromine substituents at different positions of 3-ylideneoxindole was tolerated under mild conditions, and

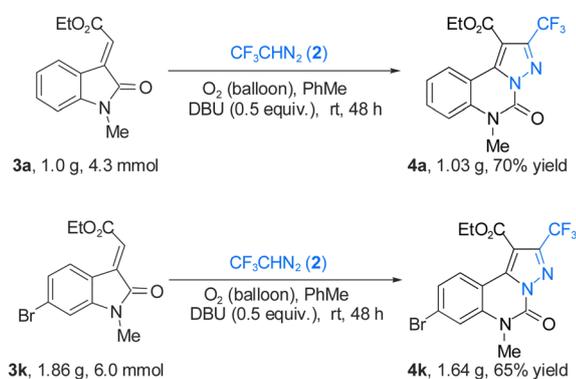




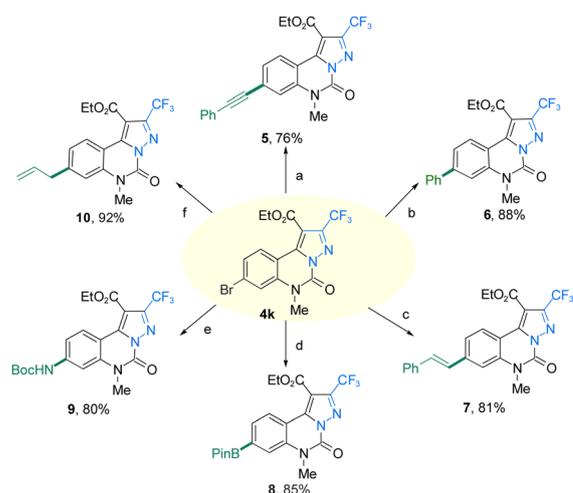
**Scheme 2** Substrate scope<sup>a</sup>. <sup>a</sup> $\text{CH}_3\text{CH}_2\text{NH}_2 \cdot \text{HCl}$  (1.5 mmol),  $\text{NaNO}_2$  (1.65 mmol) 3-acyldioxindole (0.25 mmol),  $\text{DBU}$  (0.125 mmol) were stored in  $\text{PhMe}$  (5 mL) at room temperature under an  $\text{O}_2$  atmosphere (balloon) for 48 h. <sup>b</sup>The substrate for this reaction is ethyl (*E*)-2-(2-oxoindolin-3-ylidene) acetate instead of *tert*-butyl (*E*)-3-(2-ethoxy-2-oxoethylidene)-2-oxoindoline-1-carboxylate.

the products were isolated in 35–86% yield (**4a–w**). The reaction was also compatible with disubstituted ethyl (*E*)-2-(1,5,7-trimethyl-2-oxoindolin-3-ylidene) acetate that contains an electron-donating substituent on the phenyl ring, affording **4p** in 57% yields. Steric hindrance seems to play an important factor in affecting the results, with 3-ylideneoxindole bearing different protecting groups (Ph, Bn, and allyl) on nitrogen reacting quite well with **2**, giving **4r**, **4s**, and **4t** in moderate yields. In contrast, the addition of a *Boc*-protecting group to 3-ylideneoxindole results in the removal of the *Boc*-protecting group in 37% yield (**4q**), and the same product can be obtained without any group on nitrogen, but the yield is relatively

high (71%). The 3-ylideneoxindoles bearing variation of the ester moiety (<sup>*n*</sup>Pr, <sup>*i*</sup>Pr, or <sup>*t*</sup>Bu) could also undergo this [3 + 2] cycloaddition/1,3-H shift/rearrangement/dehydrogenation cascade process, though leading to the corresponding



**Scheme 3** Gram-scale reactions.



**Scheme 4** Transformation of **4k**. (a)  $\text{Pd}(\text{PPh}_3)_2\text{Cl}_2$ ,  $\text{CuI}$ ,  $\text{Et}_3\text{N}$ , phenylacetylene,  $\text{DMF}$ , Ar,  $60\text{ }^\circ\text{C}$ , and 24 h. (b)  $\text{PhB}(\text{OH})_2$ ,  $\text{Cs}_2\text{CO}_3$ ,  $\text{Pd}(\text{OAc})_2$ , <sup>*t*</sup>BuPAD<sub>2</sub>,  $\text{DCE}$ , Ar,  $80\text{ }^\circ\text{C}$ , and 12 h. (c) Styrene,  $\text{Pd}(\text{PPh}_3)_4$ ,  $\text{PPh}_3$ ,  $\text{Et}_3\text{N}$ ,  $\text{DMF}$ , Ar,  $140\text{ }^\circ\text{C}$ , and 8 h. (d)  $\text{Pd}(\text{OAc})_2$ ,  $\text{PCy}_3$ ,  $(\text{BPin})_2$ ,  $\text{KOAc}$ ,  $\text{PhMe}$ , Ar,  $70\text{ }^\circ\text{C}$ , and 2 h. (e)  $\text{Pd}_2(\text{dba})_3$ ,  $\text{XPhos}$ ,  $\text{CsCO}_3$ ,  $\text{NH}_2\text{Boc}$ ,  $\text{PhMe}$ , Ar,  $110\text{ }^\circ\text{C}$ , and 12 h. (f)  $\text{Pd}(\text{PPh}_3)_4$ , allyltributylstannane,  $\text{DMF}$ , Ar,  $90\text{ }^\circ\text{C}$ , and 1 h.



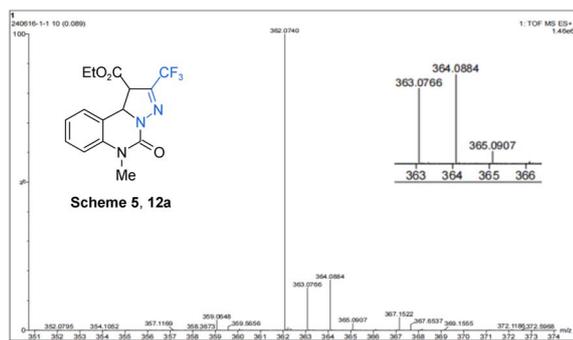
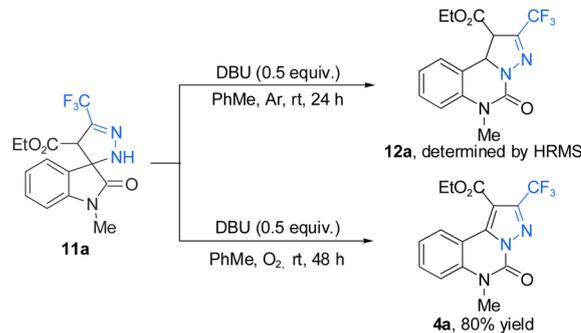


Fig. 2 HRMS of intermediate 12a.

products in moderate yields (**4u–w**). The structure of product **4a** was also unambiguously confirmed by single-crystal X-ray analysis.

To demonstrate the high efficiency of the reaction, **4a** and **4k** were scaled up under optimized conditions. As shown in Scheme 3, the final yield of **4a** is 1.02 g with a 70% yield. The yield of **4k** was 65% to 1.64 g. At the same time, the practicability of the reaction is further analyzed. The resulting product **4k** could be further transformed to **5** in 76% yield, **6** in 88% yield, **7** in 81% yield, **8** in 85% yield, **9** in 80% yield, and **10** in 92% yield through transition-metal-catalyzed Sonogashira coupling, Suzuki–Miyaura coupling, Heck coupling, Miyaura borylation, Ullmann–Ma amination and Stille coupling, respectively (Scheme 4).<sup>20</sup>

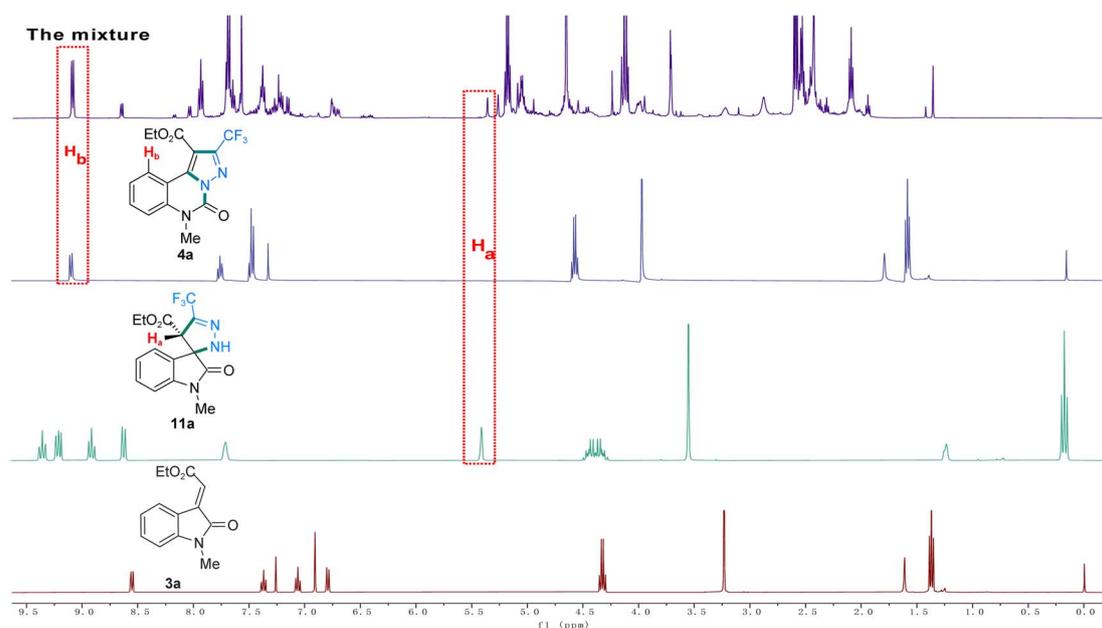
To acquire more information on the mechanism of this cascade reaction, the presence of an intermediate in the reaction liquid under argon was detected by HRMS (Fig. 2), and the template reaction was monitored by <sup>1</sup>H NMR. By monitoring the reaction mixture for 12 h, the reaction raw material **3a**, and the reaction intermediate **11a**, it was found that the corresponding

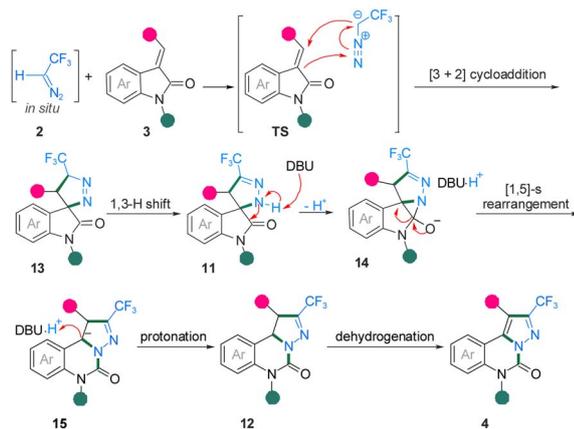


Scheme 5 Control experiments.

characteristic peak appeared in <sup>1</sup>H NMR of the mixture (Fig. 3). By monitoring <sup>1</sup>H NMR of the mixed solution 12 h after the reaction, we found that substrate **3a** was completely consumed, and the characteristic peaks of intermediate product **11a** and product **4a** appeared. To investigate the reaction mechanism based on the key intermediates **13a**, **11a**, and **12a**, three control experiments were explored. However, it is troublesome to obtain the intermediate **13a** owing to its scarcity, but the presence of **11a** can be detected by <sup>1</sup>H NMR. Notably, **11a** can transform to intermediate **12a** under the Ar atmosphere, and **4a** has been realized from **11a** in 80% yield under the O<sub>2</sub> atmosphere (Scheme 5). These results indicate that **11a**, **12a**, and **13a** are possible intermediates for the formation of **4a**.

Based on the above results and our previous reports,<sup>19c</sup> we postulate a plausible mechanism, which is depicted in Scheme 6. *In situ* generated CF<sub>3</sub>CHN<sub>2</sub> with 3-ylideneoxindoles *via* [3 + 2] cycloaddition forms intermediate **13**, followed by a 1,3-H shift process to yield the intermediate **11**. Intermediate **11** is deprotonated and closed by DBU to obtain intermediate **14**, followed by ring-opening and [1,5]-σ rearrangement to obtain

Fig. 3 <sup>1</sup>H NMR determination of the possible intermediates.



Scheme 6 Proposed reaction mechanism.

intermediate **15**. Intermediate **12** is obtained by protonation of intermediate **15**. Finally, intermediate **12** is dehydrogenated in the presence of oxygen to obtain compound **4**. In particular, due to the conjugated system of compound **4**, the dehydrogenation step might be a driving force for the transformation of intermediate **11** into fused heterocycles **4**.

Xiao and Lu's group have developed the example of a sequential [3 + 2] cycloaddition/ring contraction reaction of 3-ylideneoxindoles with *in situ*-generated  $\text{CF}_3\text{CHN}_2$ , carried out in PhMe under Ar atmosphere, to deliver  $\text{CF}_3$ -containing 3,3'-cyclopropyl spirooxindole derivatives.<sup>11</sup> In contrast, our synthetic strategy opens the route to pyrazolo[1,5-*c*]quinazolines by a 1,3-dipolar cycloaddition in the presence of DBU in PhMe under the  $\text{O}_2$  atmosphere. The desired spirooxindole **4** was afforded in moderate to 86% yields. The reaction proceeded under mild conditions with broad moderate to well yields. The mild reaction conditions, broad substrate scope, and simple and convenient handling make this method of accessing functionalized  $\text{CF}_3$ -containing N-heterocycle practical and fascinating.

## Conclusions

An atom-economical protocol of valuable and versatile pyrazolo[1,5-*c*]quinazolines has been achieved by a sequential [3 + 2] cycloaddition/1,3-H shift/rearrangement/dehydrogenation process, proceeding in moderate to good yields at room temperature. The reaction proceeded under mild conditions with good functional group tolerance, which also constructed pyrazolo[1,5-*c*]quinazolines from easily accessible 3-ylideneoxindoles and  $\text{CF}_3\text{CHN}_2$  without the need for multistep parallel synthesis. Efforts toward expanding this methodology to a broader 3-ylideneoxindole scope are currently underway. Further research on this topic with *in situ* generated  $\text{CF}_3\text{CHN}_2$  is underway in our laboratory.<sup>21</sup>

## Experimental section

### General experimental information

Unless otherwise specified, all commercially available reagents are utilized without further purification. Silica gel column

chromatography (300–400 mesh) is employed.  $^1\text{H}$ ,  $^{19}\text{F}$ , and  $^{13}\text{C}$  NMR spectra were measured on a 400, 376, and 100 MHz spectrometer, respectively.  $\text{CDCl}_3$  was used as a solvent.  $^{19}\text{F}$  chemical shifts were given as  $\delta$  in ppm downfield from  $\text{CFCl}_3$ . High-resolution mass spectra HRMS measurements were obtained on a TOF analyzer.

The preparation of 3-ylideneoxindoles was conducted following the previously reported method.

### Representative procedure for the synthesis of compound 4a

A 50 mL flask with a stir bar was charged with  $\text{CF}_3\text{CH}_2\text{NH}_2 \cdot \text{HCl}$  (1.5 mmol, 6.0 equiv.),  $\text{NaNO}_2$  (1.65 mmol, 6.6 equiv.), 0.2 mL  $\text{H}_2\text{O}$  at 0 °C for 2 h. The mixture was then dried, then **3a** (0.25 mmol, 1.0 equiv.), DBU (0.5 equiv.) and 5 mL of the drying solvent were added at room temperature under an  $\text{O}_2$  atmosphere (balloon) for 48 h (as monitored by TLC). Finally, the mixture was concentrated under reduced pressure and then purified by silica gel flash column chromatography (using a solvent system of petroleum ether/ethyl acetate = 10 : 1) to obtain the target compound **4a** (65.9 mg, yield 78%).

## Data availability

The data supporting this article have been included as part of the ESI.†

## Conflicts of interest

There are no conflicts of interest to declare.

## Acknowledgements

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## Notes and references

- (a) K. A. Lyseng-Williamson, *Drugs*, 2007, **67**, 587–597; (b) I. Egashira, F. Takahashi-Yanaga, R. Nishida, M. Arioka, K. Igawa, K. Tomooka, Y. Nakatsu, T. Tsuzuki, Y. Nakabeppu, T. Kitazono and T. Sasaguri, *Cancer Sci.*, 2017, **108**, 108–115; (c) J. B. Buse, M. A. Bethel, J. B. Green, S. R. Stevens, Y. Lokhnygina, P. Aschner, C. R. Grado, T. Tankova, J. Wainstein, R. Josse, J. M. Lachin, S. S. Engel, K. Patel, E. D. Peterson and R. R. Holman, *Diabetes Care*, 2017, **40**, 164–170; (d) M. Imamura, Y. Okamoto, T. Nishikawa, T. Yoneyama, Y. Yamasaki, J. Kawamura and Y. Kawano, *Pediatrics*, 2019, **144**, e20190319; (e) M. Kazi, A. Alqahtani, A. Ahmad, O. M. Noman, M. S. Aldughaim, A. S. Alqahtani and F. K. Alanazi, *Drug Delivery*, 2021, **28**, 100–114.
- (a) O. A. Tomashenko and V. V. Grushin, *Chem. Rev.*, 2011, **111**, 4475–4521; (b) X. Mu, S. Chen, X. Zhen and G. Liu, *Chem. – Eur. J.*, 2011, **17**, 6039–6042; (c) X. Mu, T. Wu,



- H.-Y. Wang, Y.-L. Guo and G. Liu, *J. Am. Chem. Soc.*, 2012, **134**, 878–881; (d) C. Chen, L. Chu and F.-L. Qing, *J. Am. Chem. Soc.*, 2012, **134**, 12454–12457; (e) R. Zhu and S. L. Buchwald, *J. Am. Chem. Soc.*, 2012, **134**, 12462–12465; (f) L. Chu and F.-L. Qing, *J. Am. Chem. Soc.*, 2012, **134**, 1298–1304; (g) Y. Zeng, L. Zhang, Y. Zhao, C. Ni, J. Zhao and J. Hu, *J. Am. Chem. Soc.*, 2013, **135**, 2955–2958; (h) Z.-B. He, R. Zhang, M.-Y. Hu, L.-C. Li, C.-F. Ni and J.-B. Hu, *Chem. Sci.*, 2013, **4**, 3478–3483; (i) M. Huang and C. Zhang, *Org. Lett.*, 2024, **26**, 4158–4162.
- 3 (a) J. A. Pike and J. W. Walton, *Chem. Commun.*, 2017, **53**, 9858–9861; (b) K. Hirano, T. Saito, Y. Fujihira, D. M. Sedgwick, S. Fustero and N. Shibata, *J. Org. Chem.*, 2020, **85**, 7976–7985; (c) Q. Wang, Q. Tao, H. Dong, C. Ni, X.-M. Xie and J.-B. Hu, *Angew. Chem., Int. Ed.*, 2021, **60**, 27318–27323; (d) S. Mizuta, K. Kitamura, Y. Morii, J. Ishihara, T. Yamaguchi and T. Ishikawa, *J. Org. Chem.*, 2022, **87**, 5035.
- 4 (a) Q. Glenadel, E. Ismalaj and T. Billard, *J. Org. Chem.*, 2016, **81**, 8268–8275; (b) J. Wang, X.-X. Lu, R.-P. Yang, B.-B. Zhang, Z.-H. Xiang, J.-C. Li, L. Liu, S. Chao and X. Shang, *Org. Lett.*, 2023, **25**, 8489–8494; (c) Y.-Y. Hu, X.-Q. Xu, W.-C. Deng, R.-X. Liang and Y.-X. Jia, *Org. Lett.*, 2023, **25**, 6122–6127.
- 5 (a) H. Xiao, Z. Zhang, Y. Fang, L. Zhu and C. Li, *Chem. Soc. Rev.*, 2021, **50**, 6308–6319; (b) Y. Li, X. Liang, K. Niu, J. Gu, F. Liu, Q. Xia, Q. Wang and W. Zhang, *Org. Lett.*, 2022, **24**, 5918–5923.
- 6 Z.-H. Lu, H. Liu, S.-H. Liu, X.-B. Leng, Y. Lan and Q.-L. Shen, *Angew. Chem., Int. Ed.*, 2019, **58**, 8510–8514.
- 7 J.-A. Ma and D. Cahard, *J. Fluorine Chem.*, 2007, **128**, 975–996.
- 8 (a) C.-L. Zhu, L.-J. Yang, S. Li, Y. Zheng and J.-A. Ma, *Org. Lett.*, 2015, **17**, 3442–3445; (b) Z. Chen, Y. Zheng and J.-A. Ma, *Angew. Chem., Int. Ed.*, 2017, **56**, 4569–4574; (c) S. Qin, Y. Zheng, F.-G. Zhang and J.-A. Ma, *Org. Lett.*, 2017, **19**, 3406–3409; (d) Z. Chen, N. Ren, X. Ma, J. Nie, F.-G. Zhang and J.-A. Ma, *ACS Catal.*, 2019, **9**, 4600–4608; (e) X. Zhang, Z. Liu, X. Yang, Y. Dong, M. Virelli, G. Zanoni, E. A. Anderson and X. Bi, *Nat. Commun.*, 2019, **10**, 284; (f) X.-W. Zhao, W. Q. Zhu, Y.-R. Shi, J. Zhang, H. Li, M.-G. Yang and Y. Li, *Chem. – Eur. J.*, 2024, **30**, e202304056.
- 9 P. K. Mykhailiuk, *Chem. Rev.*, 2020, **120**, 12718–12755.
- 10 (a) Y.-J. Chen, F.-G. Zhang and J.-A. Ma, *Org. Lett.*, 2021, **23**, 6062–6066; (b) A. Kumar, W. A. Khan, S. Ahamad and K. Mohanan, *J. Heterocycl. Chem.*, 2022, **59**, 607–632; (c) C.-F. Gao, Y.-J. Chen, J. Nie, F.-G. Zhang, C.-W. Cheung and J.-A. Ma, *Chem. Commun.*, 2023, **59**, 11664–11667; (d) S. Kumar, L. Fatma, N. K. Vaishnav and K. Mohanan, *J. Org. Chem.*, 2024, **89**, 761–769.
- 11 T.-R. Li, S.-W. Duan, Y.-Y. Liu, J.-R. Chen, L.-Q. Lu and W.-J. Xiao, *J. Org. Chem.*, 2014, **79**, 2296–2302.
- 12 (a) M. Bacilieri, F. Varano, F. Deflorian, M. Marini, D. Catarzi, V. Colotta, G. Filacchioni, A. Galli, C. Costagli, C. Kaseda and S. Moro, *J. Chem. Inf. Model.*, 2007, **47**, 1913–1922; (b) F. Varano, D. Catarzi, V. Colotta, D. Poli, G. Filacchioni, A. Galli and C. Costagli, *Chem. Pharm. Bull.*, 2009, **57**, 826–829.
- 13 B. Asproni, G. Murineddu, A. Pau, G. A. Pinna, M. Langgard, C. T. Christoffersen, J. Nielsen and J. Kehler, *Bioorg. Med. Chem.*, 2011, **19**, 642–649.
- 14 (a) V. Colotta, D. Catarzi, F. Varano, G. Filacchioni and L. Cecchi, *J. Med. Chem.*, 1996, **39**, 2915–2921; (b) D. Catarzi, V. Colotta, F. Varano, D. Poli, L. Squarzialupi, G. Filacchioni, K. Varani, F. Vincenzi, P. A. Borea, D. D. Ben, C. Lambertucci and G. Cristalli, *Bioorg. Med. Chem.*, 2013, **21**, 283–294.
- 15 (a) S. S. Nikam and B. E. Kornberg, *Curr. Med. Chem.*, 2001, **8**, 155–170; (b) F. Varano, D. Catarzi, V. Colotta, O. Lenzi, G. Filacchioni, A. Galli and C. Costagli, *Bioorg. Med. Chem.*, 2008, **16**, 2617–2626.
- 16 (a) M. Garg, M. Chauhan, P. K. Singh, J. M. Alex and R. Kumar, *Eur. J. Med. Chem.*, 2015, **97**, 444–461; (b) L. Liu, L. Li, S.-K. Mao, X. Wang, M.-D. Zhou, Y.-L. Zhao and H. Wang, *Chem. Commun.*, 2020, **56**, 7665–7668.
- 17 W.-W. Zhao, Y.-C. Shao, A.-N. Wang, J.-L. Huang, C.-Y. He, B.-D. Cui, N.-W. Wan, Y.-Z. Chen and W.-Y. Han, *Org. Lett.*, 2021, **23**, 9256–9261.
- 18 W.-W. Zhao, M.-Y. Tian, Y.-L. Zhou, L.-J. Liu, S.-F. Tian, C.-Y. He, X.-Z. Yang, Y.-Z. Chen and W.-Y. Han, *Angew. Chem., Int. Ed.*, 2024, **63**, e202318887.
- 19 (a) W.-Y. Han, J. Zhao, J.-S. Wang, G.-Y. Xiang, D.-L. Zhang, M. Bai, B.-D. Cui, N.-W. Wan and Y.-Z. Chen, *Org. Biomol. Chem.*, 2017, **15**, 5571–5578; (b) W.-Y. Han, J. Zhao, J.-S. Wang, B.-D. Cui, N.-W. Wan and Y.-Z. Chen, *Tetrahedron*, 2017, **73**, 5806–5812; (c) W.-Y. Han, J.-S. Wang, J. Zhao, L. Long, B.-D. Cui, N.-W. Wan and Y.-Z. Chen, *J. Org. Chem.*, 2018, **83**, 6556–6565; (d) J.-S. Wang, J. Shan, M. Bai, B.-D. Cui, N.-W. Wan, Y.-S. Wang, W.-Y. Han and Y.-Z. Chen, *Tetrahedron*, 2018, **74**, 3904–3911; (e) J.-S. Wang, K.-S. Huang, W.-Y. Han, B.-D. Cui, N.-W. Wan and Y.-Z. Chen, *Org. Lett.*, 2019, **21**, 8751–8755; (f) Z.-H. Wang, J.-H. Liu, Y.-P. Zhang, J.-Q. Zhao, Y. You, M.-Q. Zhou, W.-Y. Han and W.-C. Yuan, *Org. Lett.*, 2022, **24**, 4052–4057.
- 20 (a) D. Arora, H. Kumar, D. Malhotra and M. Malhotra, *Pharmacologyonline*, 2011, **3**, 659–668; (b) Y.-C. Fang, J.-H. Chen, R.-F. Xiu, L.-R. Zhang, F.-H. Zheng, Y.-Z. Chen, Z.-W. Gao and W.-Y. Han, *Org. Chem. Front.*, 2023, **10**, 3752–3759.
- 21 Z. Su, Z. Xie, S. Wang, N. Luo and C. Wang, *Org. Biomol. Chem.*, 2019, **17**, 7342–7351.

