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Rhodium-catalyzed annulation of hydrazines with vinylene carbonate to synthesize unsubstituted 1-aminoindole derivatives†

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Herein, we describe rhodium-catalysed C–H bond activation for [3 + 2] annulation using hydrazide and vinylene carbonate, providing an efficient method for synthesising unsubstituted 1-aminoindole compounds. Characterised by high yields, mild reaction conditions, and no need for external oxidants, this transformation demonstrates excellent regioselectivity and a wide tolerance for various functional groups.

Indole scaffolds,¹ among the most important N-heterocycles, have a wide range of applications, from pharmaceuticals and agrochemicals to renewable energy.² Particularly, 1-aminoindoles³ serve as core components of numerous bioactive molecules, such as commercial drugs like besipirdine^{4b} and indapamide,^{4c} as well as antidepressant and receptor modulators (Fig. 1). Traditional synthetic methods⁵ for these moieties are often complex, involving most synthetic routes requiring multiple steps and electrophilic *N*-amination. The necessity for strong bases, less secure *N*-aminating reagents, and harsh reaction conditions have limited their synthetic utility and practicality. Consequently, developing more efficient and economically viable synthetic strategies for the 1-aminoindole moiety has attracted significant attention.

Over the past two decades, transition metal-catalysed C–H bond activation⁶ has emerged as a valuable approach for constructing complex molecular scaffolds. Rh(III) complexes,⁷ in particular, have been instrumental in catalysing annulation reactions.⁸ However, only a few studies have been conducted on the synthesis of 1-aminoindole skeletons *via* directed C–H bond activation. Glorius *et al.*^{8a} developed an Rh(III)-catalysed oxidative annulation method using aryl-substituted diazene carboxylates and alkenes, producing C2, C3-disubstituted 1-aminoindoles (Scheme 1a, eqn (1)). Liu *et al.*^{8b} achieved the oxidative annulation of hydrazines with alkynes using 1,3-dinitrobenzene as an oxidant (Scheme 1a, eqn (2)). However, these methods require stoichiometric oxidants.

The coupling of arenes with carbene precursors⁹ in a redox-neutral manner has introduced important alternatives to oxidative annulation reactions. Wang's group^{10a} realized Rh(III)-catalyzed tandem annulation of arylhydrazines with diazo compounds as carbene precursors to yield 1-aminoindole products (Scheme 1b, eqn (3)). Zhu *et al.*^{10b} successfully used this strategy to synthesise *N*-aminoindoles *via* *N*-Boc cleavage (Scheme 1b, eqn (3)). Cui's group^{10c} he synthesis of 1-aminoindoles through a three-component cyclisation using *in situ*-formed hydrazones as guiding groups (Scheme 1b, eqn (3)). Owing to their relatively higher safety and stability, sulfoxonium ylides¹¹ have been demonstrated as carbene surrogates for diazo compounds. Xie^{12a} and Zhang^{12b} independently described a rhodium-catalyzed redox-neutral reaction involving arylhydrazines and sulfoxonium ylides to create C2-substituted 1-aminoindole derivatives (Scheme 1b, eqn (4)). Recently, Li and his colleagues¹³ reported an Rh(III)-catalyzed C–H bond activation reaction of arylhydrazines using iodonium ylides as a carbene precursor (Scheme 1b, eqn (5)). Despite the considerable progress with respect to the synthesis of 1-aminoindole derivatives, the synthesis of C2, C3-unsubstituted 1-aminoindoles through directed C–H bond activation remains underexplored (Scheme 1c, eqn (6)).

Vinylene carbonate¹⁴ is a stable and readily available substance that can be produced on an industrial scale. In 2019,

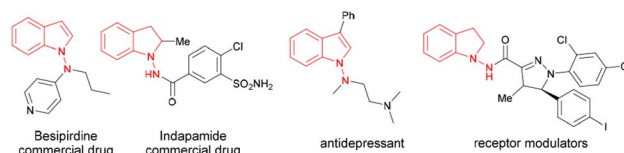


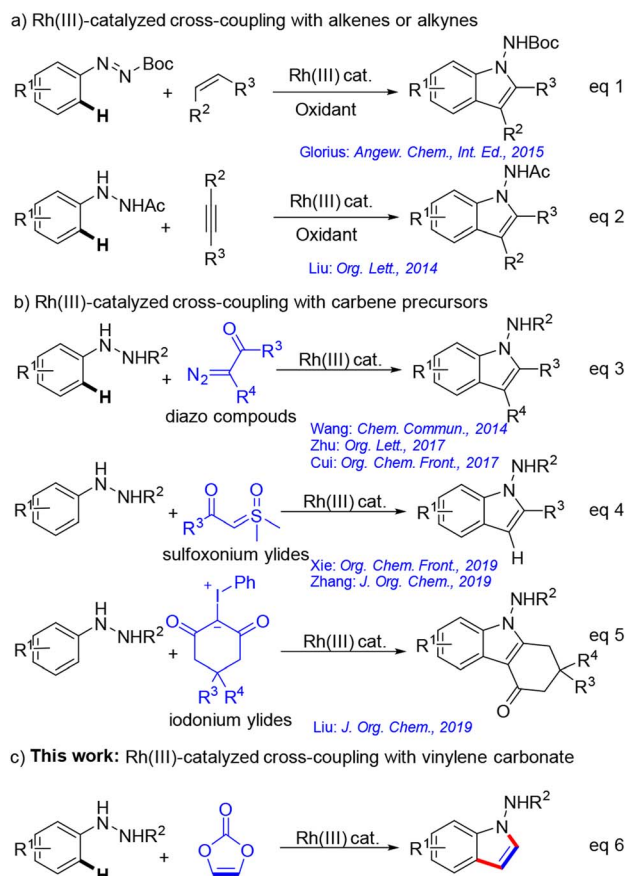
Fig. 1 Representative bioactive compounds containing 1-aminoindole skeletons.

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Scheme 1 Synthesis of 1-aminoindole compounds by C–H bond activation.

Miura's group¹⁵ pioneered the use of vinyene carbonate as an acetylene surrogate strategy in C–H functionalization and cascade annulations. Building upon this concept, the facile synthesis of various heterocycles, such as isoquinolines, isocoumarins, quinazolines, quinoline quinolone, pyrazolidinones, cinnolines, and indoles using vinyene carbonate have been realized.¹⁶ In line with our ongoing interest in heterocycle synthesis, we introduce a novel method for synthesising crucial C2, C3-unsubstituted 1-aminoindoles derivatives. This approach involves Rh(III)-catalyzed C–H bond activation and cascade annulation from arylhydrazines and vinyene carbonate (Scheme 1c).

To initiate our investigation of this reaction, we selected 1*N*'-phenylacetohydrazide (**1a**) and vinyene carbonate (**2a**) as the model substrates for the coupling reaction (Table 1). We were pleased to discover that the desired 1-aminoindole product **3aa** was obtained in 66% yield in the presence of a catalytic combination of [Cp*RhCl₂]₂ and Zn(OAc)₂ in DMF (Table 1, entry 1). NMR spectroscopy and high-resolution mass spectrometry confirmed the structure of **3aa**, which was further validated *via* X-ray crystallographic analysis¹⁷ (Fig. 2). A control experiment demonstrated the necessity of the Rh(III) catalyst; alternative catalysts such as Cp*Co(CO)I₂, [Cp*IrCl₂]₂ and [*p*-cymeneRuCl₂]₂ did not facilitate the reaction (Table 1, entries 3–5). The use of the cationic catalyst [Cp*Rh(MeCN)₃](SbF₆)₂

Table 1 Optimization of the reaction conditions^a

Entry	Catalyst	Additive	Solvents	Yield ^b (%)
1	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	DMF	66
2	[Cp*Rh(MeCN) ₃](SbF ₆) ₂	Zn(OAc) ₂	DMF	41
3	Cp*Co(CO)I ₂	Zn(OAc) ₂	DMF	nd
4	[Cp*IrCl ₂] ₂	Zn(OAc) ₂	DMF	nd
5	[<i>p</i> -CymeneRuCl ₂] ₂	Zn(OAc) ₂	DMF	nd
6	None	Zn(OAc) ₂	DMF	nd
7	[Cp*RhCl ₂] ₂	NaOAc	DMF	nd
8	[Cp*RhCl ₂] ₂	KOAc	DMF	nd
9	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	<i>t</i> -BuOH	94
10	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	MeCN	91
11	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	DME	86
12	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	DCE	85
13	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	Dioxane	80
14 ^c	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	TAA	76
15	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	Toluene	70
16	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	CH ₃ OH	nd
17 ^c	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	<i>t</i> -BuOH	66
18 ^d	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	<i>t</i> -BuOH	80
19 ^e	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	<i>t</i> -BuOH	90
20 ^f	[Cp*RhCl ₂] ₂	Zn(OAc) ₂	<i>t</i> -BuOH	90

^a **1a** (0.20 mmol), **2a** (0.40 mmol), catalyst (5 mol%), additive (20 mol%), solvent (2.0 mL), N₂, 80 °C, 16 h. ^b Isolated yield. ^c 60 °C. ^d 100 °C. ^e For 12 h. ^f For 20 h.

resulted in a decreased yield (Table 1, entry 2). Various additives were screened, but it was disappointing that no reaction occurred when NaOAc or KOAc was used (Table 1, entries 7 and 8). A range of solvents was tested, including *t*-BuOH, MeCN, DME, DCE, dioxane, TAA, toluene and CH₃OH, with *t*-BuOH proving to be the optimal solvent, achieving a 94% yield of the target product **3aa** (Table 1; entry 9). When CH₃OH was used as the solvent, the reaction did not proceed (Table 1, entry 16). The reaction efficiency was negatively affected by both increments and decrements in reaction temperature (Table 1, entries 17 and 18). Altering the reaction duration to 12 or 20 h resulted in a reduced yield (Table 1, entries 19 and 20).

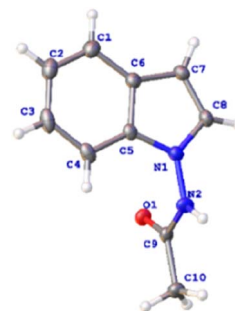
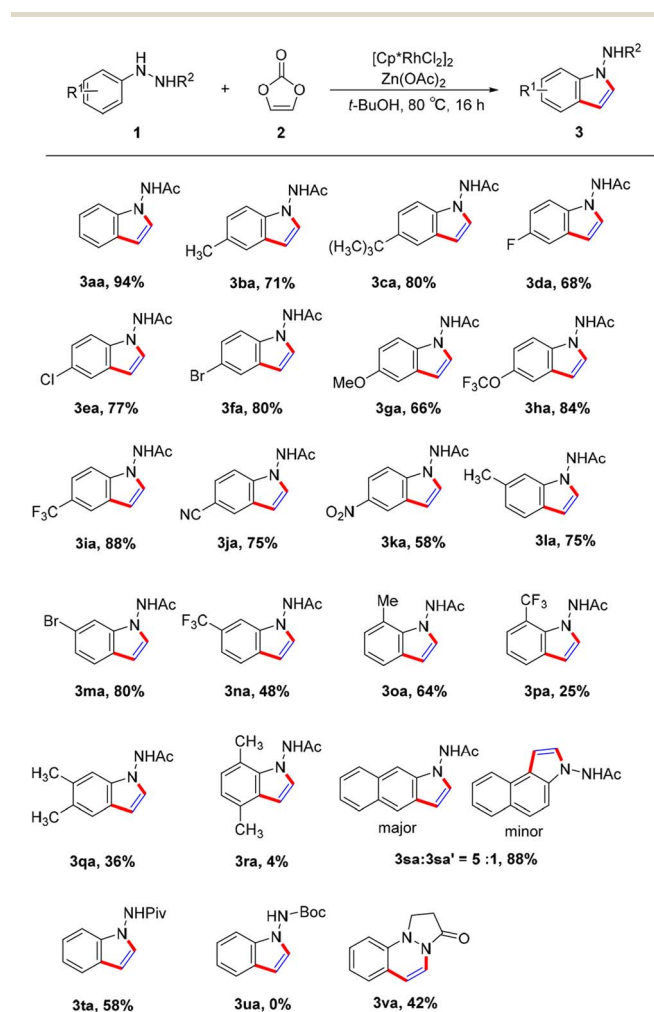


Fig. 2 Molecular structure of **3aa**.



With the optimized conditions established, we explored the substrate scope of 1-acetyl-2-phenylhydrazine (Scheme 2). The transformation exhibited a broad substrate scope, accommodating 2-acetyl-1-arylhazidines with various substituents. 2-Acetyl-1-arylhazidines, whether bearing electron-donating group (e.g., Me, OMe, and OCF₃) or electron-withdrawing groups (e.g., CF₃, CN, NO₂) at the para position, all reacted effectively with vinylene carbonate, yielding the corresponding products (**3ba–3ka**) in moderate to good yields. This functional group compatibility proves highly beneficial for synthesizing complex molecules. Furthermore, substrates with halogen substituents (e.g. F, Cl and Br) at different positions were well-tolerated, enabling further derivatisation through coupling reactions. This transformation demonstrated excellent regioselectivity, with coupling occurring at the less hindered position for *meta*-substituted substrates (**3la–3na**). The reaction seems to be sensitive to steric hindrance, as *ortho*-substituted phenylacetohydrazines (**1m–1o**) exhibited limited reactivity (**3oa–3ra**). When disubstituted derivatives were used in the reaction with vinylene carbonate, the product yield was reduced (**3qa, 3ra**).



Scheme 2 Substrate scope for hydrazines.^a Reaction conditions: **1** (0.2 mmol), **2** (0.4 mmol), [Cp**Rh*Cl₂]₂ (5 mol%), Zn(OAc)₂ (20 mol%), *t*-BuOH (2 mL), 80 °C, under N₂ for 16 h. Isolated yields after column chromatography.

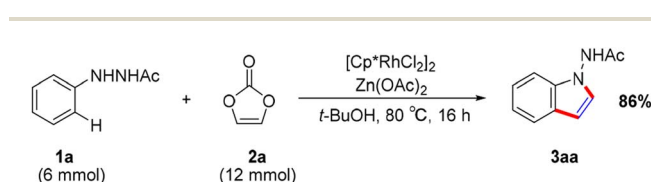
Moreover, when *N'*-(naphthalen-2-yl)acetohydrazide (**1s**) was used, the C–H bond at the 3-position, with less steric hindrance was preferred to be functionalized (**3sa : 3sa'** = 5 : 1, 88%).

Our investigation also included hydrazines with different substitutions at the R² position. A pivaloyl (Piv) group led to the formation of 1-aminoindole derivatives (**3ta**) in 58% yield, while an *N*-Boc substituent failed to produce the desired product (**3ua**). Additionally, disubstituted hydrazine **1v** was also explored and the corresponding product (**3va**) could be isolated in 42% yield.

To demonstrate the synthesis utility of our catalytic system, we performed a scaled-up reaction with 6 mmol of hydrazine (**1a**), obtaining product **3aa** in 86% yield (Scheme 3).

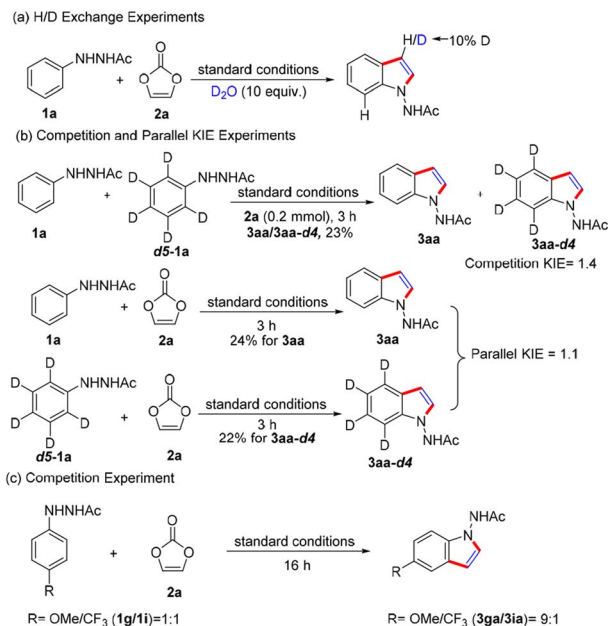
A series of experiments was conducted to investigate the reaction mechanism (Scheme 4). Initially, an H/D exchange study was carried out under standard conditions in the presence of D₂O. Only 10% deuterium was incorporated at the C3 position of **3aa** but not at other positions (Scheme 4a). The results indicate a protonation process was possibly involved in the transformation. Furthermore, a kinetic isotope effect (KIE) experiment was investigated. An intermolecular competitive KIE experiment using equivalent substrates **1a** and **1a-d5** was implemented, revealing a KIE value of 1.4 (Scheme 4b). Moreover, a KIE value of 1.1 was detected based on parallel experiments (Scheme 4b). These results suggested that the C–H bond cleavage might not be involved in the rate-determining step of the overall reaction. Additionally, an intermolecular competition reaction between **1g** and **1i** was carried out in a one-pot fashion under the optimized reaction conditions, and the products were isolated in a 9 : 1 ratio (**3ga/3ia**), demonstrating higher reactivity for the electron-rich substrate (Scheme 4c).

Based on the aforementioned experiments and previous reports,¹⁸ we propose two possible catalytic cycle pathways (Scheme 5, path a and path b). The cycle begins with the activation of a C–H bond, catalysed by rhodium(III), leading to the formation of a five-membered rhodacycle intermediate **A**. Subsequently, intermediate **A** coordinates with vinylene carbonate and undergoes migratory insertion of vinylene carbonate into the Rh–C bond, resulting in the formation of a seven-membered metallacycle complex **B**. Rhodacycle **B** may further undergo intramolecular amide attack towards Rh, yielding the six-membered **E** (path a). This is followed by C–N reductive elimination, which is succeeded by the formation of a bond into the adjacent C–O bond, giving rise to intermediate **F**. Formal β-oxygen elimination is affected to liberate the desired product (**3aa**) along with the regenerated catalyst, and the extrusion of CO₂ (path a).

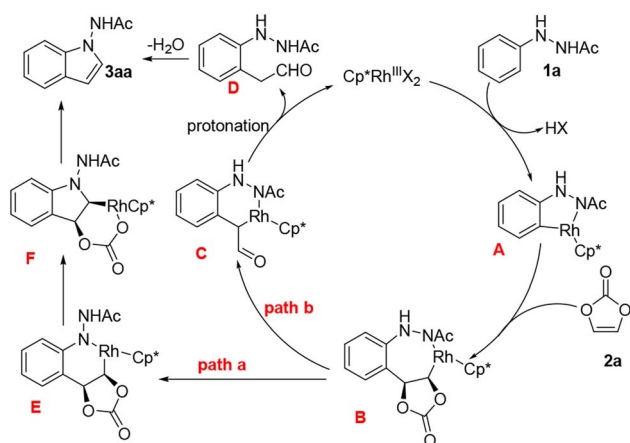


Scheme 3 Gram-scale synthesis.





Scheme 4 Mechanistic studies.



Scheme 5 Proposed mechanism.

An alternative possibility is that 1,2-Rh-C bond migration and decarboxylation may occur from intermediate **B**, resulting in the formation of intermediate **C** (path **b**). Subsequently, a protonolysis process generates the corresponding aldehyde intermediate **D**, along with the regeneration of the Cp^{*}Rh(III). After eliminating water through intramolecular condensation, the final product **3aa** is formed.

Conclusions

In summary, we developed a new method for the step-economical synthesis of C2, C3-unsubstituted 1-aminoindole derivatives. This method involves rhodium-catalysed annulation of hydrazines with vinylenecarbonate and is scalable to a gram-scale level without substantial yield loss. This protocol

showcases a broad substrate scope and exceptional tolerance for various functional groups.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- (a) T. Kawasaki and K. Higuchi, *Nat. Prod. Rep.*, 2005, **22**, 761; (b) J. A. Homer and J. Sperry, *J. Nat. Prod.*, 2017, **80**, 2178; (c) Y. C. Zhang, F. Jiang and F. Shi, *Acc. Chem. Res.*, 2020, **53**, 425; (d) Y. Meng, B. Yu, H. Huang, Y. Peng, E. Li, Y. Yao, C. Song, W. Yu, K. Zhu, K. Wang, D. Yi, J. Du and J. Chang, *J. Med. Chem.*, 2021, **64**, 925; (e) B. Prabagar, Y. Yang and Z. Shi, *Chem. Soc. Rev.*, 2021, **50**, 11249; (f) A. Dhiman, R. Sharma and R. K. Singh, *Acta Pharm. Sin. B*, 2022, **12**, 3006.
- (a) G. Zhou, D. Wu, B. Snyder, R. G. Ptak, H. Kaur and M. Gochin, *J. Med. Chem.*, 2011, **54**, 7220; (b) C. W. Lee and J. Y. Lee, *Adv. Mater.*, 2013, **25**, 5450; (c) H. Mizoguchi, H. Oikawa and H. Oguri, *Nat. Chem.*, 2014, **6**, 57; (d) I. Cho, S. K. Park, B. Kang, J. W. Chung, J. H. Kim, K. Cho and S. Y. Park, *Adv. Funct. Mater.*, 2016, **26**, 2966; (e) N. Chadha and O. Silakari, *Eur. J. Med. Chem.*, 2017, **134**, 159; (f) J. Hwang, J. Park, Y. J. Kim, Y. H. Ha, C. E. Park, D. S. Chung, S.-K. Kwon and Y.-H. Kim, *Chem. Mater.*, 2017, **29**, 2135; (g) X. Feng, D. Liao, D. Liu, A. Ping, Z. Li and J. Bian, *J. Med. Chem.*, 2020, **63**, 15115; (h) C. Qian, Z. Ma, X. Fu, X. Zhang, Z. Li, H. Jin, M. Chen, H. Jiang, X. Jia and Z. Ma, *Adv. Mater.*, 2022, **34**, 2200544; (i) X. Fu, X. Zhang, C. Qian, Z. Ma, Z. Li, H. Jiang and Z. Ma, *Chem. Mater.*, 2022, **35**, 347.
- (a) E. J. Glamkowski and P. A. Eieitano, *J. Med. Chem.*, 1979, **22**, 106; (b) G. Cignarella and P. Sanna, *J. Med. Chem.*, 1981, **24**, 1003; (c) B. A. Frontana-Urbe, C. Moinet and L. Toupet, *Eur. J. Org. Chem.*, 1999, **1999**, 419; (d) J. Chi, C. Hang, Y. Zhu and H. Katayama, *Synth. Commun.*, 2010, **40**, 1123; (e) S. S. Chaudhaery, K. K. Roy, N. Shakya, G. Saxena, S. R. Sammi, A. Nazir, C. Nath and A. K. Saxena, *J. Med. Chem.*, 2010, **53**, 6490.
- (a) K. Andersen, J. Perregaard, J. Arn, J. B. Nielsen and M. Begtrup, *J. Med. Chem.*, 1992, **35**, 4823; (b) J. T. Klein, L. Davis, G. E. Olsen, G. S. Wong, F. P. Huger, C. P. Smith, W. W. Petko, M. Cornfeldt, J. C. Wilker and R. Blitzer, *J. Med. Chem.*, 1996, **39**, 570; (c) F. Nie, J. Lu and W. Niu, *Anal. Chim. Acta*, 2005, **545**, 129; (d) H. Johansson, M. W. Boesgaard, L. Norskov-Lauritsen, I. Larsen, S. Kuhne, D. E. Gloriam, H. Brauner Osborne and D. Sejer Pedersen, *J. Med. Chem.*, 2015, **58**, 8938; (e) C.-C. Tseng, G. Baillie, G. Donvito, M. A. Mustafa, S. E. Juola, C. Zanato, C. Massarenti, S. Dall'Angelo, W. T. A. Harrison,



- A. H. Lichtman, R. A. Ross, M. Zanda and I. R. Greig, *J. Med. Chem.*, 2019, **62**, 5049.
- 5 (a) F. Melkonyan, A. Topolyan, M. Yurovskaya and A. Karchava, *Eur. J. Org. Chem.*, 2008, **2008**, 5952; (b) A. Kaga, X. Peng, H. Hirao and S. Chiba, *Chem.–Eur. J.*, 2015, **21**, 19112; (c) T. T. H. Luong, J.-D. Brion, M. Alami and S. Messaoudi, *J. Org. Chem.*, 2015, **80**, 751; (d) U. Huynh, M. Uddin, S. E. Wengryniuk, S. L. McDonald and D. M. Coltart, *Tetrahedron Lett.*, 2016, **57**, 4799; (e) H. Wang, H. Jung, F. Song, S. Zhu, Z. Bai, D. Chen, G. He, S. Chang and G. Chen, *Nat. Chem.*, 2021, **13**, 378; (f) P. Y. Vemuri and F. W. Patureau, *Org. Lett.*, 2021, **23**, 3902; (g) G. Li, L. Yang, J.-J. Liu, W. Zhang, R. Cao, C. Wang, Z. Zhang, J. Xiao and D. Xue, *Angew. Chem., Int. Ed.*, 2021, **60**, 5230.
- 6 For a recent review on C–H functionalization, see: (a) T. Gensch, M. N. Hopkinson, F. Glorius and J. Wencel-Delord, *Chem. Soc. Rev.*, 2016, **45**, 2900; (b) J. R. Hummel, J. A. Boerth and J. A. Ellman, *Chem. Rev.*, 2017, **117**, 9163; (c) Y. Park, Y. Kim and S. Chang, *Chem. Rev.*, 2017, **117**, 9247; (d) Y. Wei, P. Hu, M. Zhang and W. Su, *Chem. Rev.*, 2017, **117**, 8864; (e) Y. Yang, J. Lan and J. You, *Chem. Rev.*, 2017, **117**, 8787; (f) S. Prakash, R. Kuppasamy and C.-H. Cheng, *ChemCatChem*, 2018, **10**, 683; (g) Y. Hu, B. Zhou and C. Wang, *Acc. Chem. Res.*, 2018, **51**, 816; (h) T. Gensch, M. J. James, T. Dalton and F. Glorius, *Angew. Chem., Int. Ed.*, 2018, **57**, 2296; (i) P. Gandeepan and L. Ackermann, *Chem*, 2018, **4**, 199; (j) G. Duarah, P. P. Kaishap, T. Begum and S. Gogoi, *Adv. Synth. Catal.*, 2019, **361**, 654; (k) P. Gandeepan, T. Müller, D. Zell, G. Cera, S. Warratz and L. Ackermann, *Chem. Rev.*, 2019, **119**, 2192; (l) P. Gandeepan, T. Müller, D. Zell, G. Cera, S. Warratz and L. Ackermann, *Chem. Rev.*, 2019, **119**, 2192; (m) S. V. Kumar, S. Banerjee and T. Punniyamurthy, *Org. Chem. Front.*, 2020, **7**, 1527; (n) W. Ma, Ni. Kaplaneris, X. Fang, L. Gu, R. Mei and L. Ackermann, *Org. Chem. Front.*, 2020, **7**, 1022; (o) S. K. Sinha, S. Guin, S. Maiti, J. P. Biswas, S. Porey and D. Maiti, *Chem. Rev.*, 2021, **122**, 5682; (p) T. Rogge, N. Kaplaneris, N. Chatani, J. Kim, S. Chang, B. Punji, L. L. Schafer, D. G. Musaev, J. Wencel-Delord, C. A. Roberts, R. Sarpong, Z. E. Wilson, M. A. Brimble, M. J. Johansson and L. Ackermann, *Nat. Rev. Methods Primers*, 2021, **1**, 43; (q) B. Liu, A. M. Romine, C. Z. Rubel, K. M. Engle and B.-F. Shi, *Chem. Rev.*, 2021, **121**, 14957; (r) L. Guillemard, N. Kaplaneris, L. Ackermann and M. J. Johansson, *Nat. Rev. Chem.*, 2021, **5**, 522; (s) T. Dalton, T. Faber and F. Glorius, *ACS Cent. Sci.*, 2021, **7**, 245; (t) S. K. Sinha, S. Guin, S. Maiti, J. P. Biswas, S. Porey and D. Maiti, *Chem. Rev.*, 2021, **122**, 5682; (u) T. Dalton, T. Faber and F. Glorius, *ACS Cent. Sci.*, 2021, **7**, 245; (v) B. Liu, A. M. Romine, C. Z. Rubel, K. M. Engle and B.-F. Shi, *Chem. Rev.*, 2021, **121**, 14957; (w) T. Rogge, N. Kaplaneris, N. Chatani, J. Kim, S. Chang, B. Punji, L. L. Schafer, D. G. Musaev, J. Wencel-Delord, C. A. Roberts, R. Sarpong, Z. E. Wilson, M. A. Brimble, M. J. Johansson and L. Ackermann, *Nat. Rev. Methods Primers*, 2021, **1**, 43; (x) R. Logeswaran and M. Jeganmohan, *Adv. Synth. Catal.*, 2022, **364**, 2113; (y) R. Maayuri and P. Gandeepan, *Org. Biomol. Chem.*, 2023, **21**, 441.
- 7 (a) T. Satoh and M. Miura, *Chem.–Eur. J.*, 2010, **16**, 11212; (b) D. A. Colby, A. S. Tsai, R. G. Bergman and J. A. Ellman, *Acc. Chem. Res.*, 2012, **45**, 814; (c) N. Kuhl, N. Schroder and F. Glorius, *Adv. Synth. Catal.*, 2014, **356**, 1443; (d) G. Song and X. Li, *Acc. Chem. Res.*, 2015, **48**, 1007; (e) B. Ye and N. Cramer, *Acc. Chem. Res.*, 2015, **48**, 1308; (f) K. Shin, H. Kim and S. Chang, *Acc. Chem. Res.*, 2015, **48**, 1040; (g) T. Gensch, M. N. Hopkinson, F. Glorius and J. Wencel-Delord, *Chem. Soc. Rev.*, 2016, **45**, 2900.
- 8 (a) D. Zhao, S. Vásquez-Céspedes and F. Glorius, *Angew. Chem., Int. Ed.*, 2015, **54**, 1657; (b) D. Y. Li, H. J. Chen and P. N. Liu, *Org. Lett.*, 2014, **16**, 6176.
- 9 For selected recent reviews on C–H/carbene precursors, see: (a) F. Hu, Y. Xia, C. Ma, Y. Zhang and J. Wang, *Chem. Commun.*, 2015, **51**, 7986; (b) Y. Xia, D. Qiu and J. Wang, *Chem. Rev.*, 2017, **117**, 13810; (c) S. Nunewar, S. Kumar, S. Talakola, S. Nanduri and V. Kanchupalli, *Chem.–Asian J.*, 2021, **16**, 443; (d) S. Kumar, V. Borkar, M. Mujahid, S. Nunewar and V. Kanchupalli, *Org. Biomol. Chem.*, 2022, **21**, 24.
- 10 (a) Y. Liang, K. Yu, B. Li, S. Xu, H. Song and B. Wang, *Chem. Commun.*, 2014, **50**, 6130; (b) P. Shi, L. Wang, S. Guo, K. Chen, J. Wang and J. Zhu, *Org. Lett.*, 2017, **19**, 4359; (c) Z. Yang, X. Lin, L. Wang and X. Cui, *Org. Chem. Front.*, 2017, **4**, 2179.
- 11 (a) M. Barday, C. Janot, N. R. Halcovitch, J. Muir and C. Aïssa, *Angew. Chem., Int. Ed.*, 2017, **56**, 13117; (b) Y. Xu, X. Zhou, G. Zheng and X. Li, *Org. Lett.*, 2017, **19**, 5256; (c) C. You, C. Pi, Y. Wu and X. Cui, *Adv. Synth. Catal.*, 2018, **360**, 4068; (d) S. Ji, K. Yan, B. Li and B. Wang, *Org. Lett.*, 2018, **20**, 5981; (e) C. Hong, X. Jiang, S. Yu, Z. Lu and Y. Zhang, *Chin. J. Org. Chem.*, 2021, **41**, 888; (f) A. Singh, S. Kumar and C. M. R. Volla, *Org. Biomol. Chem.*, 2022, **21**, 879.
- 12 (a) W. Xie, X. Chen, J. Shi, J. Li and R. Liu, *Org. Chem. Front.*, 2019, **6**, 2662; (b) N. Lv, Z. Chen, Z. Liu and Y. Zhang, *J. Org. Chem.*, 2019, **84**, 13013.
- 13 H. Li, H. Gu, Y. Lu, N. Xu, N. Han, J. Li, J. Liu and J. Liu, *J. Org. Chem.*, 2019, **84**, 13013.
- 14 (a) X. Gao, R. Zhai, X. Chen and S. Wang, *Chin. J. Org. Chem.*, 2023, **43**, 3119; (b) Y. Ge, Q. Yan and J. Nan, *Org. Chem. Front.*, 2023, **96**, 5717.
- 15 K. Ghosh, Y. Nishii and M. Miura, *ACS Catal.*, 2019, **9**, 11455.
- 16 (a) X. Li, T. Huang, Y. Song, Y. Qi, L. Li, Y. Li, Q. Xiao and Y. Zhang, *Org. Lett.*, 2020, **22**, 5925; (b) G. Mihara, K. Ghosh, Y. Nishii and M. Miura, *Org. Lett.*, 2020, **22**, 5706; (c) K. Ghosh, Y. Nishii and M. Miura, *Org. Lett.*, 2020, **22**, 3547; (d) L. Wang, K.-C. Jiang, N. Zhang and Z.-H. Zhang, *Asian J. Org. Chem.*, 2021, **10**, 1671; (e) C. Wang, X. Fan, F. Chen, P.-C. Qian and J. Cheng, *Chem. Commun.*, 2021, **57**, 3929; (f) J. Nan, Q. Ma, J. Yin, C. Liang, L. Tian and Y. Ma, *Org. Chem. Front.*, 2021, **8**, 1764; (g) X. Huang, Y. Xu, J. Li, R. Lai, Y. Luo, Q. Wang, Z. Yang and Y. Wu, *Chin. Chem. Lett.*, 2021, **32**, 3518; (h) J. Singh, S. Sharma and A. Sharma, *J. Org. Chem.*, 2021, **86**, 24; (i)



- J. Nan, J. Yin, X. Gong, Y. Hu and Y. Ma, *Org. Lett.*, 2021, **23**, 8910; (j) M. S. Park, K. Moon, H. Oh, J. Y. Lee, P. Ghosh, J. Y. Kang, J. S. Park, N. K. Mishra and I. S. Kim, *Org. Lett.*, 2021, **23**, 5518; (k) Y. Hu, J. Nan, J. Yin, G. Huang, X. Ren and Y. Ma, *Org. Lett.*, 2021, **23**, 8527; (l) F.-P. Hu, X.-G. Zhang, M. Wang, H.-S. Wang and G.-S. Huang, *Chem. Commun.*, 2021, **57**, 11980; (m) N. Li, X. Zhang and X. Fan, *Tetrahedron Lett.*, 2022, **103**, 153984; (n) P. Kumar and M. Kapur, *Chem. Commun.*, 2022, **58**, 4476; (o) S. Kim, H. K. Park, J. Y. Kang, N. K. Mishra and I. S. Kim, *Synthesis*, 2022, **54**, 4461; (p) Y. Yu, Y. Wang, B. Li, Y. Tan, H. Zhao, Z. Li, C. Zhang and W. Ma, *Adv. Synth. Catal.*, 2022, **364**, 838; (q) G. Huang, J. T. Yu and C. Pan, *Eur. J. Org. Chem.*, 2022, e202200279; (r) J. L. Song, L. Xiao, S. Y. Chen, Y. C. Zheng, Y. Z. Liu, S. S. Zhang and B. Shu, *Adv. Synth. Catal.*, 2023, **365**, 1457; (s) S. Jothi Murugan and M. Jeganmohan, *J. Org. Chem.*, 2023, **88**, 1578; (t) S. Zhang, S. Hu, K. Wang, Z. Yang, H. Liu and J. Wang, *Adv. Synth. Catal.*, 2023, **365**, 238; (u) V. Kumar and P. Gandeepan, *Eur. J. Org. Chem.*, 2023, e202300914.
- 17 CCDC 2302860 for compounds **3aa**.
- 18 (a) B. Shen, S. Liu, L. Zhu, K. Zhong, F. Liu, H. Chen, R. Bai and Y. Lan, *Organometallics*, 2020, **39**, 2813; (b) J. Kitano, Y. Nishii and M. Miura, *Org. Lett.*, 2022, **24**, 5679.

