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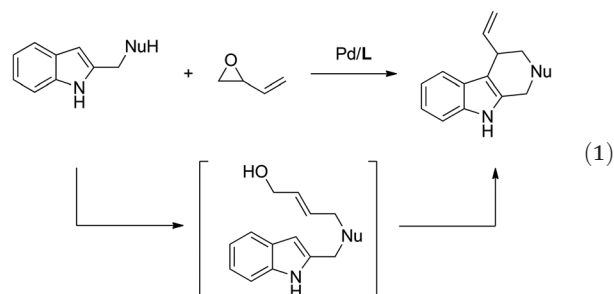
Pd-catalyzed cascade allylic alkylation and dearomatization reactions of indoles with vinyloxirane†

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We have developed Pd-catalyzed intermolecular Friedel–Crafts-type allylic alkylation and allylic dearomatization reactions of substituted indoles bearing a nucleophilic group with vinyloxirane, providing an efficient method to synthesize structurally diverse tetrahydrocarboline and spiroindolenine derivatives under mild conditions.

Substituted indole nucleus and polycyclic skeletons embedded with indoline moieties represent important structural motifs in numerous natural products and pharmaceuticals.¹ Meanwhile, transition-metal catalyzed Friedel–Crafts-type allylic alkylation² and allylic dearomatization³ reactions of indoles have proved to be efficient and successful strategies for the synthesis of structurally diverse indolines in good yields with high diastereoselectivity and enantioselectivity. However, most of the successful examples to date have employed allyl carbonates as electrophiles. Allylic alcohols as electrophiles in allylic substitution reactions in the presence of suitable promoters were reported in the last decade.⁴ The Tamaru group⁵ and Trost group⁶ respectively reported Pd-catalyzed allylic dearomatization of indoles with allylic alcohols in the presence of trialkylborane. After that, Bandini and coworkers⁷ elegantly described the use of allylic alcohols in the catalytic and enantioselective Friedel–Crafts alkylation reaction in the presence of chiral gold complexes. Moreover, the Carreira⁸ group disclosed that branch allylic alcohols were suitable allylic precursors under acidic conditions. Recently, we have developed a Ru-catalyzed⁹ intermolecular dearomatization of indoles with allylic alcohols *via* a cascade sequence including the allylic dearomatization/cyclization/allylic amination reaction. In addition, we realized an iridium-catalyzed¹⁰ intermolecular allylic dearomatization reaction of substituted indoles using the Carreira ligand and Fe(OTf)₂ as an additive.

In addition to these reports on employing allylic alcohols as suitable electrophiles in allylic substitution reactions, vinyloxirane under palladium catalysis could *in situ* generate an allylic alcohol upon the attack by a suitable nucleophile.¹¹ Inspired by these elegant reports, we envisioned the utilization of vinyloxirane might enable a cascade reaction with indole bearing a nucleophile (eqn (1)). Herein, we describe such a Pd-catalyzed cascade allylic alkylation reaction of dimethyl malonate tethered indoles with vinyloxirane, including the intermolecular nucleophilic ring-open reaction of vinyloxirane and the subsequent intramolecular allylic alkylation and dearomatization reactions.

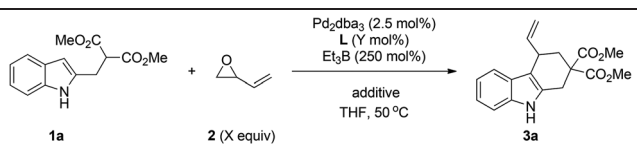


We initiated our investigation with the optimization of the reaction of dimethyl 2-((1*H*-indol-2-yl)methyl) malonate **1a** and vinyloxirane **2**. First, various ligands were examined in the presence of Pd₂dba₃ with Et₃B as a promoter in THF at 50 °C. As shown in Table 1, when the monodentate ligand Ph₃P or P(OPh)₃ was used, no reaction was observed (entries 1 and 2, Table 1). Notably, bidentate ligands such as dppe and dppp could afford the product **3a** in the same yield (entries 3 and 4, Table 1, 79% yield as determined by GC-MS). However, the desired product **3a** and substrate **1a** have a similar polarity and therefore cause the difficulty in separation in the case of incomplete conversion. Dppp was used as a preferred ligand because substrate **1a** could not be consumed completely using dppe as the ligand. By reducing the loading of vinyloxirane, better yield could be obtained (entry 7, Table 1). In the presence of 2.5 mol% of Pd₂dba₃ and 5.5 mol% of dppp, we then

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Table 1 Optimization of the reaction conditions^a


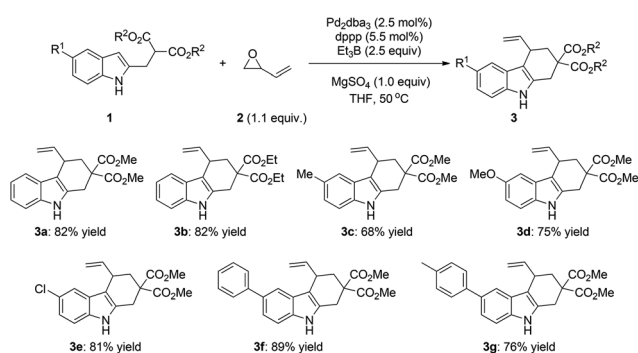
Entry	Ligand	X	Y	Additive	Yield ^b (%)
1	PPh ₃	1.3	11	—	Trace
2	P(OPh) ₃	1.3	11	—	Trace
3	dppp	1.3	5.5	—	79 ^c
4	dppp	1.3	5.5	—	79 ^c (64)
5	dppb	1.3	5.5	—	71 ^c
6	dppf	1.3	5.5	—	19 ^c
7	dppp	1.1	5.5	—	69
8	dppp	2.0	5.5	—	32
9 ^d	dppp	1.1	5.5	Na ₂ SO ₄	79
10 ^d	dppp	1.1	5.5	CaCl ₂	20
11 ^d	dppp	1.1	5.5	MgSO ₄	83
12 ^e	dppp	1.1	5.5	MgSO ₄	82

^a Reaction conditions: 0.2 mmol of **1a**, 2.5 mol% Pd₂dba₃, 0.5 mL Et₃B (1 M in THF) in THF (2.0 mL) at 50 °C. ^b Isolated yield. ^c Determined by GC-MS (normal dodecane as the internal standard). ^d 5.0 equiv. additive was used. ^e 1.0 equiv. additive was used.

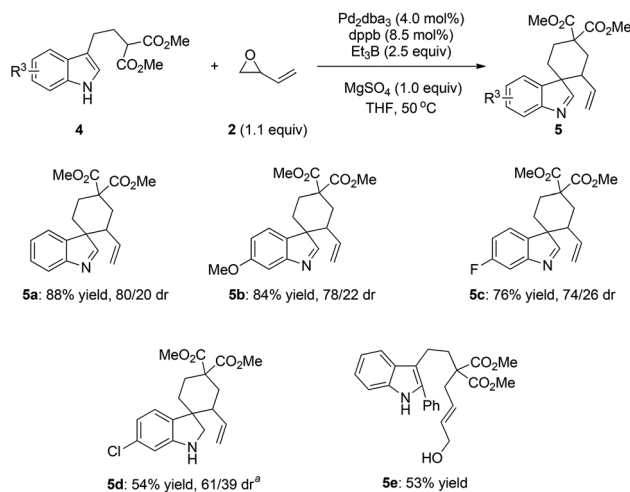
tested the effects of various additives such as Na₂SO₄, CaCl₂ and MgSO₄ (entries 9–12, Table 1). The reaction with MgSO₄ proceeded smoothly, providing the desired product **3a** with the best result (82% yield, entry 12, Table 1).

Under the optimized reaction conditions (entry 12, Table 1), we next turned our attention to explore the substrate scope of the reaction. As summarized in Scheme 1, substrates bearing different ester groups could be tolerated, giving the corresponding products in 82% yield in both cases (**3a**, **3b**, Scheme 1). The reactions of 5-substituted indole substrates with either an electron-donating group (Me, OMe, Ph) or an electron-withdrawing group (Cl) proceeded smoothly under the optimal conditions, affording the desired products in good yields (68–89%).

By taking advantage of the nucleophilicity of the C-3 position of indoles, we have developed an allylic dearomatization



Scheme 1 The substrate scope for intermolecular Friedel–Crafts-type allylic alkylation reaction. Reaction conditions: 0.2 mmol of **1**, 0.22 mmol of **2**, 2.5 mol% Pd₂dba₃, 5.5 mol% dppp, 0.5 mL Et₃B (1 M in THF) and 0.2 mmol of MgSO₄ in THF (2.0 mL) at 50 °C.



Scheme 2 The substrate scope for intermolecular allylic dearomatization reaction. Reaction conditions: 0.2 mmol of **4**, 0.22 mmol of **2**, 4.0 mol% Pd₂dba₃, 8.5 mol% dppb, 0.5 mL Et₃B (1 M in THF) and 0.2 mmol of MgSO₄ in THF (2.0 mL) at 50 °C. ^a Reaction conditions: 7.5 mol% Pd₂dba₃, 16 mol% dppb, 0.5 mL Et₃B (1 M in THF) and 0.2 mmol of MgSO₄ in THF (2.0 mL) at 50 °C, and then reduced by NaBH₃CN.

reaction of indoles with an intramolecular design. The Pd-catalyzed allylic cascade reaction of C-3 substituted indoles with vinyl oxirane has also been successful in a dearomatization fashion. The results are summarized in Scheme 2. With dppb as the ligand, the reactions of substrates **4a** and **4b**, bearing an electron-donating group on the indole core, could give the desired products with satisfactory yields (84–88% yields) and moderate diastereoselectivity (**5a**: 80/20, **5b**: 78/22, Scheme 2). For the 6-F substituted indole **4c**, moderate yield and diastereoselectivity could also be achieved (76% yield, 74/26 dr). Notably, substrate **4d** and its dearomatized product have a similar polarity, which led to the difficulty in product separation. To address this problem, a one-pot reaction including an *in situ* reduction was carried out to convert the indolenine to the corresponding indoline (54% yield with 61/39 dr). Interestingly, for the more bulky substrate **4e**, allylic alcohol **5e** was obtained in 53% yield under the same reaction conditions. These results indicated that the current Pd-catalyzed cascade reaction firstly generates the corresponding allylic alcohol.

In conclusion, we have developed Pd-catalyzed intermolecular Friedel–Crafts-type allylic alkylation and allylic dearomatization of indoles with vinyl oxirane through a cascade sequence. These protocols provide a rapid construction of structurally diverse tetrahydrocarboline and spiroindolenine derivatives under mild conditions.

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