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A ruthenium(II)-catalyzed C–H allenylation-based approach to allenic acids†

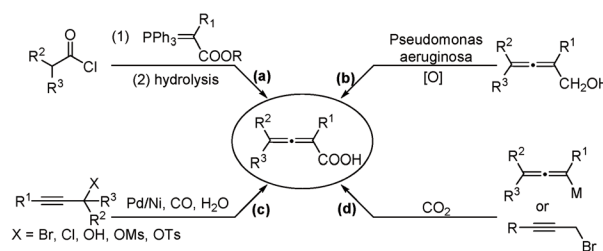
Xiaoyan Wu, Junjie Fan, Chunling Fu and Shengming Ma*

A Ru(II)-catalyzed direct access to various functionalized allenic acids via C–H allenylation of readily available aryl carboxylic acids with propargylic acetates is reported. Axially chiral allenic acids could be obtained in high ee by using optically active propargylic acetates through a chirality transfer strategy.

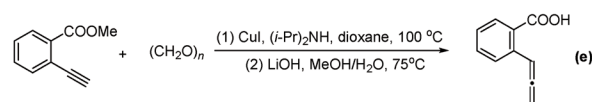
Allene moieties are not only present in natural products but also in precious building blocks due to their unique structures and multiple reactive sites.¹ Allene chemistry has experienced an explosion during the last few decades.² Thus, the synthesis of functionalized allenes is of crucial importance. Of particular interest is the synthesis of synthetically versatile allenic acids.³ A common approach to 2,3-allenoic acids is the hydrolysis of 2,3-allenoates, which suffers from poor step-economy and a selectivity issue of forming allenic acids and 3-alkynoic acids (Scheme 1a).⁴ The only example of the oxidation of allenols is realized through microbial transformation (Scheme 1b).⁵ Pd- or Ni-catalyzed carboxylation of propargylic compounds with CO in the presence of water (Scheme 1c)⁶ and the carboxylation of 2-alkynyl bromides or allenylmetallic reagents with CO₂ (Scheme 1d)⁷ have also been reported. Crabbé homologation of *o*-methoxycarbonylphenylacetylene with paraformaldehyde results in the formation of methyl 2-propadienylbenzoate, which undergoes hydrolysis to afford the corresponding allenic acid (Scheme 1e).⁸ The limitations are harsh conditions and the use of toxic carbon monoxide, stoichiometric amounts of reductants and limited substrates. On the other hand, C–H activation has been proven to be a powerful tool in synthetic chemistry because of the atom- and step-economy.⁹ The synthesis of allenes based on C–H activation is undoubtedly an ideal strategy.¹⁰ We reasoned that the most straightforward approach to allenic acids would be the use of benzoic acids with carboxylic acid acting as an inherent directing group.¹¹ Herein, we wish to report the realization of Ru-catalyzed synthesis of allenic acids via direct C–H allenylation of benzoic acids (Scheme 1f).

Our initial attempt began with benzoic acid **1a** and propargylic acetate **2a** in the presence of [Ru(*p*-cymene)Cl₂]₂ and NaOAc at 50 °C using toluene as the solvent. To our delight, the monoallenylation product **3aa** was generated in 7% yield together with 67% recovery of **2a** (Table 1, entry 1). We then investigated the effect of the solvent (Table 1, entries 2–7). The reaction could proceed in dioxane, DCE, CH₃CN, THF, and even in water, albeit affording the monoallenylation product **3aa** and the double allenylation product **4aa** in rather low yields (Table 1, entries 2–6). To our surprise, the yield could be greatly improved when the reaction was conducted in MeOH: 36% yield of the monoallenylation product **3aa** and 16% yield of the double allenylation product **4aa** were obtained (Table 1, entry 7). We next examined a series of additives as shown in entries 8–13: when K₂CO₃ was employed, the reaction gave a 64% combined

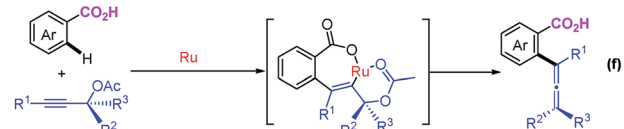
common approaches to 2,3-butadienoic acid:



reported synthesis of 2-propadienylbenzoic acid:



This work: allenic acids via C–H allenylation

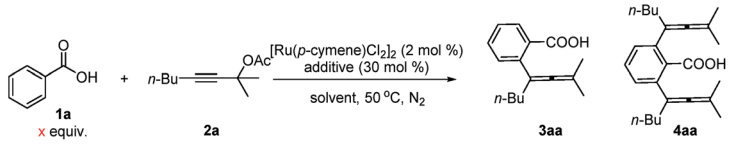


Scheme 1 Approaches to allenic acids.

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Table 1 Optimization of the *ortho*-allenylation of benzoic acid **1a**^a


Entry	<i>x</i>	Solvent	Additive	Time (h)	Combined yield (3aa/4aa) ^b (%)	Recovery of 2a ^b (%)
1	1.5	Toluene	NaOAc	46	7 (7/0)	67
2	1.5	Dioxane	NaOAc	46	15 (12/3)	20
3	1.5	DCE	NaOAc	46	14 (14/0)	24
4	1.5	CH ₃ CN	NaOAc	46	27 (23/4)	26
5	1.5	THF	NaOAc	46	30 (23/7)	6
6	1.5	H ₂ O	NaOAc	46	19 (12/7)	23
7	1.5	MeOH	NaOAc	46	52 (36/16)	13
8	1.5	MeOH	NaOAc	12	57 (39/18)	29
9	1.5	MeOH	K ₃ PO ₄	12	41 (30/11)	7
10	1.5	MeOH	<i>t</i> -BuONa	12	22 (18/4)	21
11	1.5	MeOH	Na ₂ CO ₃	12	57 (40/17)	18
12	1.5	MeOH	Cs ₂ CO ₃	12	60 (42/18)	20
13	1.5	MeOH	K ₂ CO ₃	12	64 (45/19)	27
14	1.5	EtOH	K ₂ CO ₃	12	69 (36/33)	9
15	2.0	MeOH	K ₂ CO ₃	12	66 (48/18)	16
16	2.4	MeOH	K ₂ CO ₃	12	63 (50/13)	16
17	2.6	MeOH	K ₂ CO ₃	12	72 (58/14)	20
18	3.0	MeOH	K ₂ CO ₃	12	61 (52/9)	21
19 ^c	2.6	MeOH	K ₂ CO ₃	12	67 (56/11)	18
20 ^c	2.6	MeOH	—	12	0	42

^a The reaction was conducted with **1a**, **2a** (0.2 mmol), [Ru(*p*-cymene)Cl₂]₂ (0.004 mmol), and an additive (0.06 mmol) in a solvent (0.5 mL) at 50 °C.

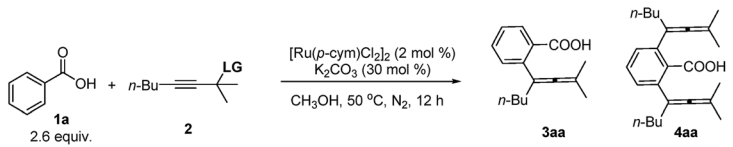
^b Determined by ¹H NMR analysis using CH₂Br₂ as the internal standard. ^c In air.

yield of **3aa** and **4aa** (Table 1, entry 13). The reaction in EtOH under optimal conditions led to increased combined yield but a lower selectivity of **3aa/4aa** (Table 1, entries 13–14). When 2.6 equiv. of benzoic acid were used, the yield was the highest with a selectivity of 58/14 (Table 1, entry 17). When the reaction was conducted in air, the influence was negligible (Table 1, entry 19). In the absence of the base, we only observed the decomposition of propargylic acetate.

We further investigated the effect of the leaving group (LG) by studying the reaction of benzoic acid **1a** with several propargylic alcohol derivatives and found that OAc was still the best leaving group (Table 2).

With the optimized reaction conditions in hand, the scope of the reaction was investigated at the 1.0 mmol scale (eqn (1) and (2) and Table 3). The parent benzoic acid **1a** afforded the monoallenylation product **3aa** in 55% yield together with the diallenylation product **4aa** in 10% yield (eqn (1)). 4-

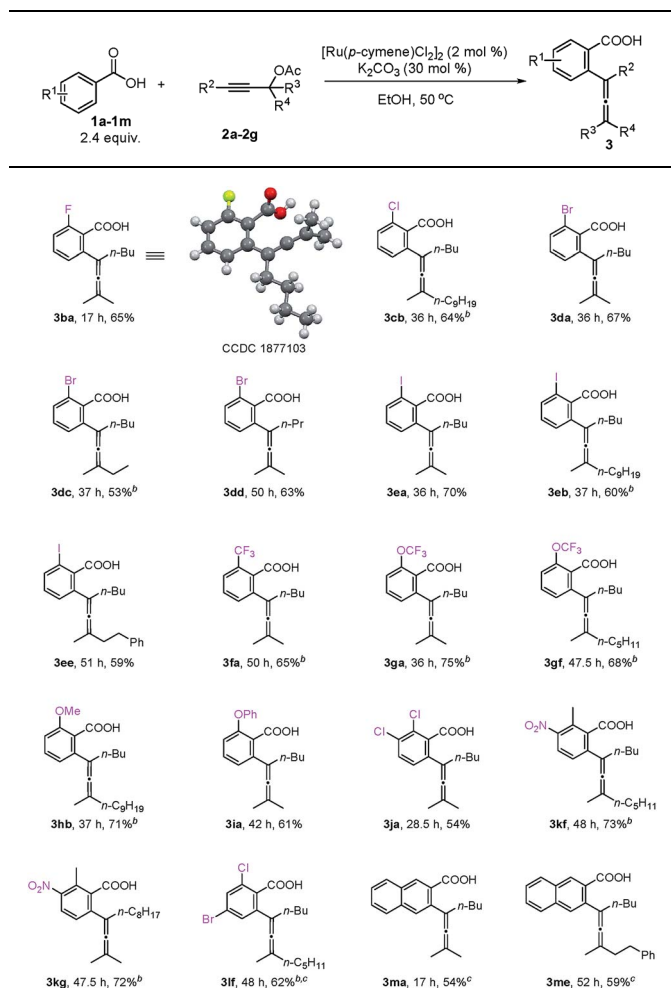
Table 2 Effect of the leaving groups



Entry	LG	Combined yield (3aa/4aa) ^a (%)	Recovery of 2a ^a (%)
1	OMe (2a ₁)	0 (—/—)	59
2	OCO ₂ Me (2a ₂)	54 (40/14)	9
3	OCOEt (2a ₃)	57 (47/10)	20
4	OBoc (2a ₄)	61 (47/14)	21
5	OAc (2a)	72 (58/14)	20

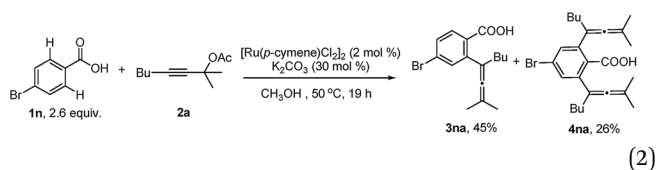
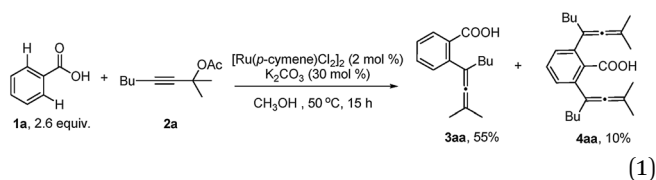
^a Determined by ¹H NMR analysis using CH₂Br₂ as the internal standard.



Table 3 Reaction scope^a

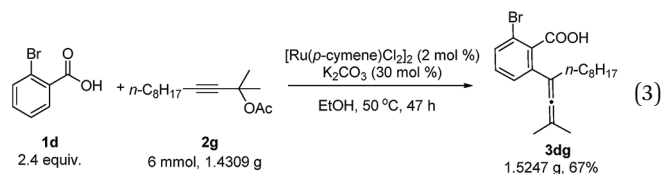
^a The reaction was conducted with **1** (2.4 mmol), **2** (1.0 mmol), $[\text{Ru}(\text{p-cymene})\text{Cl}_2]_2$ (0.02 mmol), and K_2CO_3 (0.3 mmol) in EtOH (2.5 mL) at 50 °C. ^b 4 mol% $[\text{Ru}(\text{p-cymene})\text{Cl}_2]_2$. ^c 5.0 mL of EtOH as the solvent.

Bromobenzoic acid **1n** was converted to the monoallenylation product **3na** (45% yield) and the bisallenylation product **4na** (26% yield) under the standard conditions (eqn (2)).



For mono-*o*-substituted benzoic acids, electron withdrawing groups, such as halogen atoms (including fluorine, chlorine, bromine, and iodine), CF_3 , and OCF_3 , were all well tolerated (Table 3, **3ba–3gf**). The structure of **3ba** was confirmed by X-ray diffraction study.¹² Mono-*o*-substituted benzoic acids containing the electron-donating groups methoxy and phenoxy afforded allenylation products **3hb** in 71% yield and **3ia** in 61% yield, respectively. 2,3-Dichlorobenzoic acid (**3ja**), 2-methyl-3-nitrobenzoic acid (**3kf** and **3kg**) and 2-chloro-4-bromobenzoic acid (**3lf**) were also allenylated in moderate to good yields. Notably, when the reaction was conducted with β -naphthoic acid, which has more than one C–H bond, 3-allenylation products **3ma** and **3me** were obtained exclusively. The scope of C–H allenylation with regard to propargylic acetates was also investigated affording **3cb**, **3nb**, **3dc**, **3dd**, **3ee**, **3le**, **3kf**, **3gf**, or **3kg** smoothly.

A gram scale reaction using 2-bromobenzoic acid **1d** with **2g** afforded the allenylation product **3dg** in 67% yield (eqn (3)).



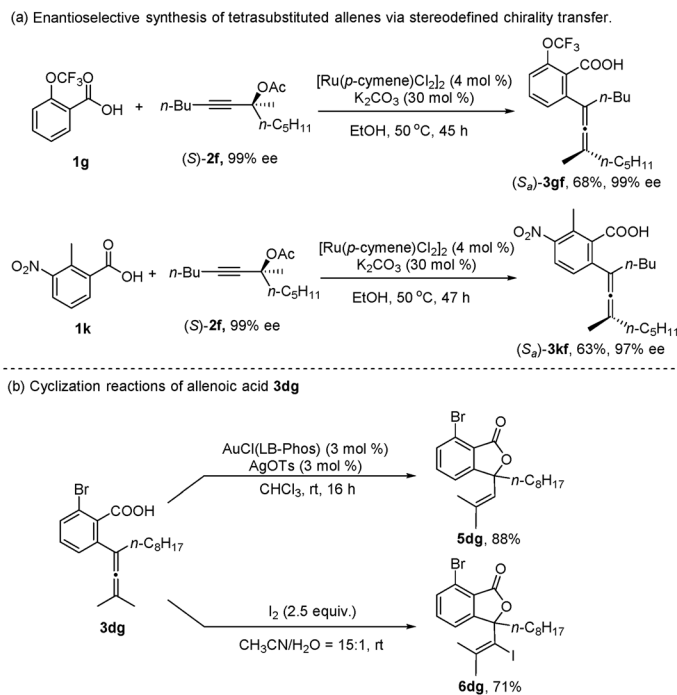
In addition, when the optically active acetate (*S*)-**2f** (99% ee) was applied, axially chiral allenylated acids (*S_a*)-**3gf** (99% ee) and (*S_a*)-**3kf** (97% ee) could be obtained with highly efficient chirality transfer (Scheme 2a). This method may open a new avenue for developing practical and synthetically useful methodologies for the synthesis of optically active allenylated acids. Meanwhile, this result indicated that the coordination of acetates and ruthenium species dictated the regioselectivity of alkyne insertion and the stereoselectivity of β -OAc elimination.

To further explore the synthetic utility of this method, several synthetic applications were studied (Scheme 2b). The allenylated acid **3dg** was easily transformed into the lactone **5dg** by treatment with $\text{AuCl}(\text{LB-Phos})$ and AgOTf .¹³ This allenylated acid may also undergo an iodolactonization reaction with iodine to afford **6dg** in 71% yield.

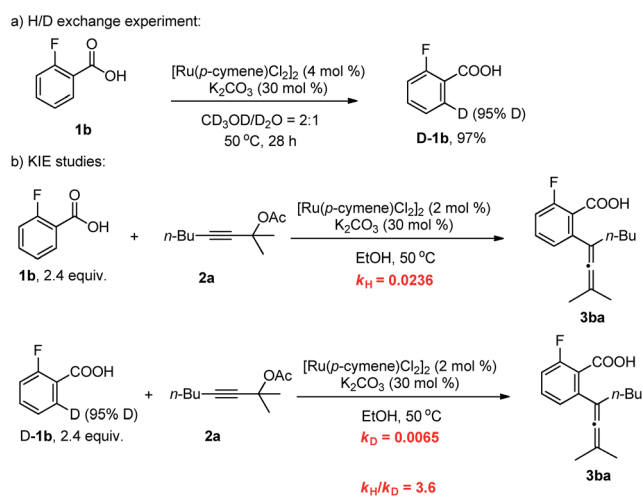
To gain insight into the mechanism of this methodology, several control experiments were carried out. Firstly, when 2-fluorobenzoic acid **1b** was added to a mixture of CD_3OD and D_2O (2 : 1), the corresponding benzoic acid **D-1b** with 95% deuterium incorporation was obtained (Scheme 3a), indicating that the C–H activation step was reversible in the catalytic system. Subsequently, the parallel reactions of **1b** and **D-1b** with **2a** were conducted. We measured the reaction rate (*k*) of both **1b** and **D-1b** by monitoring the concentration of the product **3ba** by NMR from 2.5 h to 8 h (Scheme 3b and Fig. 1). Then, the primary kinetic isotope effect of 3.6 was observed. These results suggest that C–H bond cleavage is the rate-determining step.¹⁴

In addition, a first-order dependence of the initial rate on the amount of the Ru catalyst was established (Fig. 2a, see the





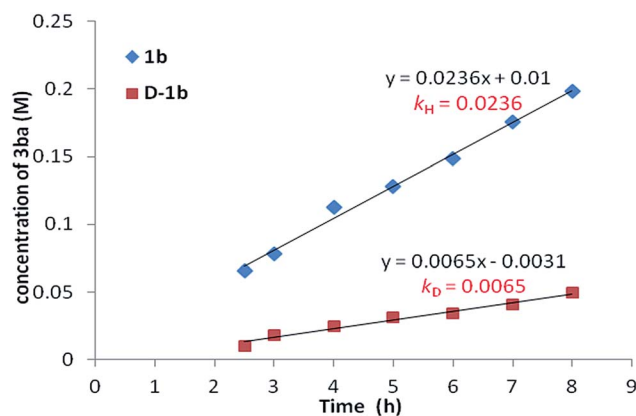
Scheme 2 Synthetic applications.



Scheme 3 Mechanistic studies.

ESI⁺ for details). The reaction orders of each reactant were also measured by using 2-fluorobenzoic acid **1b** and propargylic acetate **2a**. Both **1b** and **2a** follow the first-order reaction rate law, according to the linear relationship with $\ln([\mathbf{1b}])$ vs. reaction time: $\ln([\mathbf{1b}]) = -k_1t + \ln[\mathbf{1b}_0]$ (Fig. 2b) and $\ln([\mathbf{2a}]) = -k_2t + \ln[\mathbf{2a}_0]$ (Fig. 2c). Based on these data, we may give the rate equation as $d[\mathbf{3ba}]/dt = k[\text{Ru}] \cdot [\mathbf{1b}] \cdot [\mathbf{2a}]$.

To further understand the role of benzoic acid on the reaction, four experiments were conducted by using different molar ratios of 2-fluorobenzoic acid **1b** vs. propargylic acetate **2a** (Fig. 2d). The yield vs. time profile is almost the same in the initial four hours, indicating that the loading of benzoic acid has a very limited effect on the formation of the final

Fig. 1 Plot of the concentrations of **3ba** vs. time.

product; the excess benzoic acid did not accelerate the formation of the product greatly.¹⁵ In addition, we observed that the reaction failed to afford the expected product in the absence of K_2CO_3 , indicating a CMD process for the C–H cleavage. However, due to its catalytic nature, the role of benzoic acid as a Brønsted acid to promote the insertion process from **Int 2** to **Int 3** cannot be excluded.¹⁶

Based on these investigations above, the proposed catalytic cycle is illustrated in Scheme 4. Firstly, the C–H activation step leads to the formation of the cyclic intermediate **Int 1** via a CMD process. Subsequently, **Int 2** is generated by the coordination of the carbonyl unit in acetate with the Ru in the cycloruthenated species, which subsequently undergoes the *syn*-insertion of a C–C triple bond to afford **Int 3**. After a *syn*- β -OAc elimination step, the allenylation product was generated and the ruthenium



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- 12 **3ba**: C₁₆H₁₉FO₂, MW = 262.32, monoclinic, space group *P121/c* 1, final *R* indices [*I* > 2σ(*I*)], *R*1 = 0.0602, w*R*2 = 0.1483; *R* indices (all data), *R*1 = 0.0962, w*R*2 = 0.1764; *a* = 10.7724(13) Å, *b* = 15.7829(12) Å, *c* = 9.9065(12) Å, α = 90.00°, β = 116.778(15)°, γ = 90.00°, *V* = 1503.7(3) Å³, *T* = 296(2) K, *Z* = 4, reflections collected/unique 5576/2735 (*R*_{int} = 0.0294), number of observations [*>*2σ(*I*)]: 1722, parameters: 179. Supplementary crystallographic data have been deposited at the Cambridge Crystallographic Data Centre, CCDC 1877103.†
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