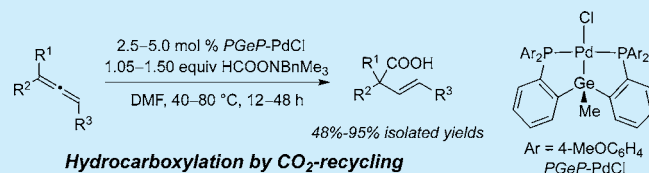# Use of Formate Salts as a Hydride and a CO$_2$ Source in *PGeP*-Palladium Complex-Catalyzed Hydrocarboxylation of Allenes

Chuan Zhu, Jun Takaya, and Nobuharu Iwasawa*

Department of Chemistry, Tokyo Institute of Technology, O-okayama, Meguro-ku, Tokyo 152-8551, Japan

Ⓢ *Supporting Information*

ABSTRACT: Use of formate salts as a hydride as well as a CO$_2$ source was achieved in a *PGeP*-palladium complex-catalyzed hydrocarboxylation of allenes through a highly efficient decarboxylation−carboxylation process. This reaction proceeds under mild conditions and provides an alternative strategy for utilizing formate salts as a C1 source.

2.5–5.0 mol % *PGeP*-PdCl
1.05–1.50 equiv HCOONBnMe$_3$

DMF, 40–80 °C, 12–48 h

48%–95% isolated yields

Ar = 4-MeOC$_6$H$_4$
PGeP-PdCl

Hydrocarboxylation by CO$_2$-recycling

Utilization of renewable chemical feedstock for the synthesis of various value-added fine chemicals is an important strategy in synthetic chemistry.[1] In this regard, formic acid and its conjugated base, formate salt, are a promising renewable C1 resource because they are cheap, abundant, and readily available from a biomass process[2] and hydrogenation of CO$_2$.[3] Traditionally, formic acid or formate salts are employed as a reductant in transition-metal catalyzed transfer hydrogenation, in which they act as a dihydrogen or hydride donor with release of CO$_2$ as an innocent coproduct.[4] In contrast, use of formic acid or its salts as a C1 source through a transition-metal catalyzed carbon−carbon bond forming reaction has rarely been achieved;[5,6] Simonato et al. reported hydrocarboxylation of alkenes,[7] and several groups reported hydroxycarbonylation of aryl and vinyl halides.[8,9] In these reactions, CO is generated *in situ* from formic acid or formate salts, and they generally require excess formic acid or its salts and harsh conditions to realize efficient conversion. Thus, development of a more atom-economical and efficient protocol for utilizing formic acid or its salts as a C1 source is still highly desirable. Herein, we demonstrate a new approach for using formate salt as a C1 source through Pd-catalyzed hydrocarboxylation of allenes, in which the formate salt is disassembled and added to allenes as hydride and CO$_2$ with high efficiency. This reaction realized a new CO$_2$-recycling protocol with formate salts for the first time, providing a facile method for the synthesis of synthetically useful β,γ-unsaturated carboxylic acids.[10]

Previously, we have reported *PSiP*-palladium complex catalyzed-hydrocarboxylation of allenes and 1,3-dienes with CO$_2$ using AlEt$_3$ or its analogues as a stoichiometric reductant.[11,12] Toward development of a new and efficient utilization of formic acid or its salts as a C1 source, we envisaged the possibility of using formate salt not only as a hydride donor instead of aluminum reagent but also as a CO$_2$ source in the hydrocarboxylation reaction as shown in Scheme 1. We expected that a palladium formate complex **A** bearing a group 14 element-bridged pincer type ligand[13] would undergo decarboxylation to produce a palladium hydride complex **B** and CO$_2$ reversibly.[14] Hydropalladation of an allene with **B** would

Scheme 1. Expected Catalytic Cycle
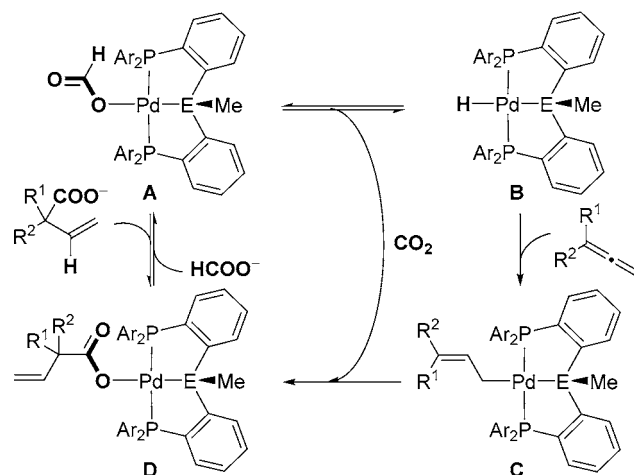
afford a σ-allylpalladium complex **C**, which could react with the released CO$_2$ to afford a palladium carboxylate **D**.[15] Finally anion exchange with formate would give the desired hydrocarboxylation product and regenerate the palladium formate **A**. The most difficult challenge of this strategy is the recycling of CO$_2$ through the reaction with the σ-allylpalladium intermediate **C**. There exists only a catalytic amount of CO$_2$ in the reaction vessel[16] whereas previously reported carboxylation reactions are usually carried out with a large excess of CO$_2$ gas.[17]

We began our studies employing allene **2a** as a model substrate and HCOONBnMe$_3$ as a formate salt. In the presence of 5 mol % of palladium complex **1a** bearing a *PSiP*-pincer type ligand, the reaction of **2a** with 1.05 equiv of formate proceeded at room temperature in DMF to give β,γ-unsaturated carboxylic acid **3a** in 39% yield (Table 1, entry 1). Interestingly, a screening of catalysts revealed that palladium complex **1b** having a *PGeP*-pincer type ligand improved the yield significantly (83%, entry 2), which could be attributed to the

Table 1. Optimization of Reaction Conditions[a]

1a: E = Si, Ar = Ph, X = OTf
1b: E = Ge, Ar = Ph, X = OTf
1c: E = Ge, Ar = 4-MeOC$_6$H$_4$, X = OTf
1d: E = Ge, Ar = 4-MeOC$_6$H$_4$, X = Cl

entry	catalyst	Y	temp	yield/%[b]
1	5 mol % **1a**	NBnMe$_3$	rt	39
2	5 mol % **1b**	NBnMe$_3$	rt	83
3	5 mol % **1c**	NBnMe$_3$	rt	92
4	2.5 mol % **1c**	NBnMe$_3$	40 °C	92
5	2.5 mol % **1d**	NBnMe$_3$	40 °C	93(92)[c]
6	2.5 mol % **1d**	N^{n}Bu$_4$	40 °C	85
7	2.5 mol % **1d**	NMe$_4$	40 °C	83
8	2.5 mol % **1d**	K	40 °C	48
9	2.5 mol % **1d**	Cs	40 °C	66

[a]All reactions were run using 0.2 mmol of **2a** (0.2 M). [b]Determined by ^{1}H NMR using 1,1,2,2-tetrachloroethane as an internal standard. [c]Isolated yield.

increased stability of the corresponding allylpalladium intermediate (entries 3 and 4).[18,19] Finally *PGeP*-Pd complex **1d** bearing electron-donating phosphorus atoms was found to be the most effective catalyst (entry 5). Among ammonium formates, the benzyl(trimethyl)ammonium salt gave the highest yield (entries 5−7). It should be noted that the reaction also proceeded with potassium and cesium formate, which are cheap and commercially available formate salts, to give **3a** in moderate to good yield under similar conditions (entries 8 and 9).

With the optimized conditions in hand, we then investigated the substrate scope of the hydrocarboxylation reaction (Table 2). 1,1-Disubstituted allenes were suitable substrates for this reaction to give α-quaternary-β,γ-unsaturated carboxylic acids selectively. A variety of functional groups were tolerated, such as alkene, silyl ether, ester, imide, carbamate, and ketal, affording functionalized carboxylic acid derivatives in good to high yield (entries 1−3, 6, 8, and 9). It should be noted that substrates **2e** and **2h** with an unmasked hydroxyl group and an acidic amide proton could undergo this hydrocarboxylation efficiently (entries 4 and 6). Also, allene **2f** which contains an aryl halide substitution is applicable in this reaction (entry 5). Moreover, ketone **2k** and even aldehyde **2l** which are sensitive to the nucleophile were compatible with the reaction conditions (entries 10 and 11). The use of prochiral substrate **2m** provided the desired product in 85% yield with high diastereoselectivity (93:7 dr, entry 12). Interestingly, when aryl-substituted allene **2n** was employed in this hydrocarboxylation, the regioselectivity of carboxylation completely changed to give linear product **5n** instead of a branched one at 80 °C (entries 13). Besides 1,1-disubstituted allenes, the reaction works with 1,3-disubstituted and monosubstituted allenes successfully. Hydrocarboxylation of **2o** and **2q** delivers the β,γ-unsaturated carboxylic acids **4o** and **4q** in good yield as a single isomer although phenyl-substituted allene **2p** afforded linear product **5p** selectively (entries 14−16). In contrast to the previous system using AlEt$_3$ as the reductant, isomerization of the alkene moiety of products was not observed at all in this reaction

Table 2. Substrate Scope[a,b]

[a]Conditions: **2** (0.2 mmol), HCOONBnMe$_3$ (0.21 mmol), **1d** (0.005 mmol), DMF (0.2 M). [b]Isolated yields. [c]Isolated as methyl ester after treatment with TMSCHN$_2$. [d]**1d** (5 mol %) was used. [e]HCOONBnMe$_3$ (0.3 mmol) was used. [f]dr = 93:7.

probably due to the strong base or acid-free conditions with formate.[20] Finally, it was found that the reaction of 3-methyl-1,2-butadiene **2r** with commercially available, cheap HCOOK proceeded efficiently on 10 mmol scale to give 2,2-dimethylbut-3-enoic acid **3r** in 90% yield, demonstrating the practical utility of this reaction for carboxylic acid synthesis (Scheme 2). This is the first example of a highly efficient, atom economical

Scheme 2. Practical Hydrocarboxylation with Potassium Formate
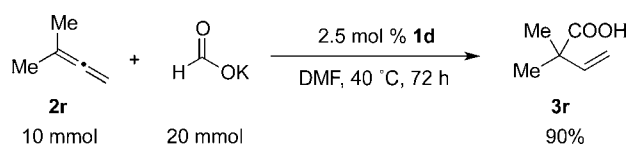
hydrocarboxylation of unsaturated hydrocarbons using formate as both the reductant and CO_2 source. It should also be noted that the reaction greatly improves substrate generality with various functional groups due to the mild reactivity of formate compared with previously reported hydrocarboxylation reactions using a metallic reductant.

A set of ^{13}C-labeling experiments with $H^{13}COONBnMe_3$ provided strong support for the initially proposed mechanism as follows.[21] First, the reaction of allene **2a** with $H^{13}COONBnMe_3$ under optimized conditions afforded the β,γ-unsaturated carboxylic acid, which was isolated as its methyl ester **4a** in 93% yield (Table 3, entry 1). ^{13}C-incorporation at

Table 3. ^{13}C-Labeling Experiments[a]

entry	atmosphere	yield/%[b]	% [13]C of 4a
1	Ar	93	>98%
2	CO	62	>96%
3	CO_2	36	ca. 13%

[a]All reactions were carried out with 0.2 mmol of **2a**, 0.21 mmol of $H^{13}COONBnMe_3$, and 0.005 mmol of **1d**. [b]Isolated yields.

the carboxyl group of **4a** was determined to be >98% by MS, demonstrating that the carboxyl group in the product originated from formate through C−C bond formation. Second, the common carbonylation pathway involving decomposition of formate to CO and H_2O is ruled out by a labeling experiment under a CO atmosphere, which afforded >96% ^{13}C-labeled product **4a** in good yield, clearly demonstrating there is no participation of carbon monoxide as the C1 source in the catalytic cycle (entry 2).[7] Finally, the reaction with $H^{13}COONBnMe_3$ under nonlabeled CO_2 (ca. 6 equiv to **2a**) gas resulted in a dramatic decrease of product yield and ^{13}C-incorporation (36%, ca. 13% [13]C, entry 3). The considerable exchange of ^{13}C and ^{12}C can be explained by generation of free [13]CO_2 from ^{13}C-formate and reaction of allylpalladium with excess [12]CO_2 in the reaction vessel through the Pd-mediated decarboxylation−carboxylation process. Moreover, the inhibition effect of external CO_2 gas on the reaction rate implies decarboxylation of palladium formate is reversible. This equilibrium was also confirmed by treatment of $H^{13}COONBnMe_3$ with 2.5 mol % **1d** under CO_2 in DMF, resulting in ca. 45% loss of ^{13}C content of the formate employed after 6 h at room temperature.[22] These experimental results clearly support the proposed CO_2-recycling mechanism in Scheme 1, in which formate works as a hydride and CO_2 source through reversible decarboxylation of formate palladium complex **A** and successive formation of σ-allylpalladium intermediate **B** followed by nucleophilic addition to the released CO_2. In this reaction, the *PGeP*-pincer ligand played a crucial role to realize this unprecedented CO_2-recycling

mechanism through generation and reaction of a carbon nucleophile. It is also noted that the carboxylation reaction proceeded quite efficiently with a catalytic amount of CO_2 generated in the reaction medium. More detailed investigations on the reaction mechanism and the role of the pincer ligand are in progress.

In conclusion, we have developed the first general protocol for formate-mediated hydrocarboxylation without additional CO_2. In this reaction, abundant and cheap formate salt was employed as both hydride and CO_2 donors, demonstrating new utilization of formate as a C1 source in synthetic chemistry. The reaction displayed broad functional group compatibility, with alcohol, amide, aldehyde, and ketone substituents tolerated. Isotope labeling experiments supported the unprecedented CO_2-recycling mechanism through generation and reaction of a carbon nucleophile. Further mechanistic study and application of this protocol to other substrates are ongoing in our laboratory.

ASSOCIATED CONTENT

Supporting Information

Preparative methods and spectral and analytical data. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*E-mail: niwasawa@chem.titech.ac.jp.

Notes

The authors declare no competing financial interest.

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(16) Here "a catalytic amount" means that there exists a maximum of an equimolar amount of CO_2 compared to the Pd catalyst in the reaction medium during the reaction.

(17) Related CO_2 recycling protocols have been reported by Bäckvall et al. and Yoshida et al. in the Pd-catalyzed decarboxylation of propargyl- or allylcarbonate derivatives. In these reactions the released CO_2 is captured by a highly reactive anionic oxygen or nitrogen nucleophile. See: (a) Bäckvall, J.-E.; Granberg, K. L.; Heumann, A. *Isr. J. Chem.* **1991**, *31*, 17. (b) Yoshida, M.; Ihara, M. *Angew. Chem., Int. Ed.* **2001**, *40*, 616. (c) Yoshida, M.; Fujita, M.; Ishii, T.; Ihara, M. *J. Am. Chem. Soc.* **2003**, *125*, 4874. (d) Yoshida, M. *Chem. Pharm. Bull.* **2012**, *60*, 285 and references cited therein.

(18) Formation of palladium black was observed in the reaction with *PSiP*-Pd complex **1a**, which is likely due to the decomposition of the highly reactive allyl *PSiP*-Pd intermediate. As a comparison, there was no obvious formation of palladium black in the reaction with *PGeP*-Pd complex **1b**.

(19) We have examined the reaction with a typical PCP-Pd, PNP-Pd, Pd/DPEphos and common Pd catalysts such as $PdCl_2(PPh_3)_2$ and $[Pd(\pi\text{-allyl})Cl]_2$; however, no product was obtained.

(20) With the *PSiP*-Pd/AlEt$_3$ system the reaction of mono- and 1,3-disubstituted allenes gives β,γ-unsaturated carboxylic acid together with a small amount of its regioisomer and α,β-unsaturated carboxylic acid as the product. For details, see ref 11.

(21) The ^{13}C-content in $H^{13}COONBnMe_3$ was determined by ^1H and ^{13}C NMR. The ^{13}C-content in **4a** was calculated by EI-MS. See Supporting Information for details.

(22) For details, see Supporting Information.