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Hydrocarboxylation of Allenes with CO_2 Catalyzed by Silyl Pincer-Type Palladium Complex

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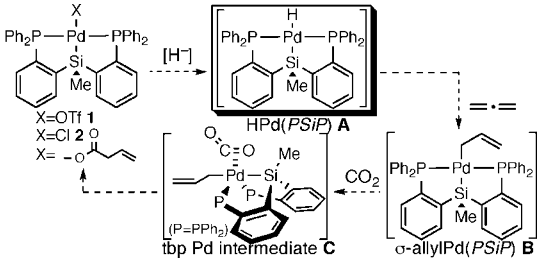
Carboxylation of carbon nucleophiles under atmospheric pressure of CO_2 as an electrophile is highly valuable as a straightforward method for the synthesis of carboxylic acids, and development of its catalytic variant has been a great challenge in synthetic chemistry.[1] Recently several groups including ours reported transition metal catalyzed carboxylation of less nucleophilic organometallic reagents such as allylstannanes,[2] aryl- or alkenylboronic esters,[3] or organozincs;[4] however, such methodologies usually require preparation of these reagents mostly from the corresponding organic halides. Thus, catalytic generation of nucleophilic organometallic species from easily available unsaturated hydrocarbons would be highly desirable from the standpoint of the atom economical synthetic methodology; however, such catalysis is mostly limited to that based on Ni(0)-promoted oxidative cyclization of rather specific unsaturated hydrocarbons.[5,6] Herein we report a new approach to the catalytic CO_2-fixation reaction through the generation of σ-allyl palladium species via hydropalladation of allenes, followed by its nucleophilic addition to CO_2 by using a tridentate silyl pincer-type palladium hydride complex **A** as the active catalyst in the presence of an appropriate reducing agent.[7,8]

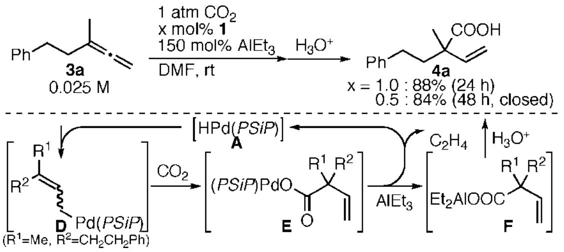
We have designed the reaction based on the following expectations (Scheme 1).[9] First, the allylpalladium intermediate **B**, generated by hydropalladation of an allene, would take the form of a σ-allyl complex due to its *PSiP*-tridentate structure and is expected to display nucleophilicity for carboxylation.[10] Second, the nucleophilicity of σ-allylpalladium intermediate **B** would be enhanced due to the strong electron-donating nature and trans influence of the silicon atom at the center of the tridentate pincer backbone.[11] Third, a rather strained square planar structure of the *PSiP*-linkage tethered by the benzene ring would facilitate structural change to a trigonal bipyramidal geometry, allowing coordination of CO_2 to realize facile carboxylation as depicted in **C**. Finally, the pincer structure of the complex would retard Pd(0) liberation and avoid side reactions such as oxidative cyclization of allenes promoted by Pd(0).[12]

Examination of appropriate reductants was carried out with 3-methyl-5-phenyl-1,2-pentadiene **3a** under 1 atm of CO_2 in the presence of 1 mol% of *PSiP*-Pd triflate complex **1** in several solvents.[13,14] After extensive screening of reaction conditions, the use of 150 mol% of $AlEt_3$ turned out to be the choice of the reducing agent, affording the desired β,γ-unsaturated carboxylic acid **4a** with a quaternary carbon center at the α-position of the carbonyl in 88% yield (Scheme 2).[15,16] The catalyst loading could be reduced to 0.5 mol% without decreasing the yield (84% after 48 h). Although higher temperature was required, $ZnEt_2$ also showed good activity as a reductant to give **4a** in 84% yield at 60 °C.[17] γ-Substituted β,γ-unsaturated carboxylic acid, formed by carboxylation at the less substituted carbon of the allyl palladium intermediate, was not observed. The reaction is believed to start with generation of silyl pincer-type palladium hydride complex **A** via transmetalation of $AlEt_3$ to **1** followed by β-hydride elimination. Hydrometalation of 1,1-disubstituted allene preferentially affords less congested σ-allyl palladium intermediate **D**, which then undergoes nucleophilic addition to CO_2 at the γ-position of the palladium regioselectively to give carboxylate palladium complex **E**. Finally, a transmetalation/β-hydride elimination sequence regenerates catalytically active palladium hydride **A** and releases the carboxylation product as its Al-salt **F** (Scheme 2).[18]

Scheme 1. Utilization of Silyl Pincer-Type Pd Complex



Scheme 2. **1**-Catalyzed Hydrocarboxylation of Allene



Generality of 1,1-disubstituted allenes was investigated by using 150 mol% of $AlEt_3$ as the reductant in DMF (Table 1). The reaction of 3-methyl-1,2-butadiene **3b**, Ph-conjugated allene **3c**, and *exo*-vinylidenecycloheptane **3g** proceeded smoothly to give corresponding α-quaternary β,γ-unsaturated carboxylic acids in good yield as a single regioisomer (entries 1−2, 6). Another feature of this carboxylation reaction is its high compatibility with various functionalities. Silyl ether **3d**, ester **3e**, ketal **3i**, and carbamate **3h** were successfully converted to the corresponding functionalized carboxylic acids in moderate to excellent yield by using only 1 mol% of catalyst (entries 3, 4, 7, and 8). More importantly, alkene and ketone moieties were not affected under the reaction conditions (entries 5 and 9). High diastereoselectivity was attained when allene **3k** was used (entry 10).[19] Thus, this carboxylation reaction of 1,1-disubstituted allenes provided a highly efficient entry to synthetically useful α-quaternary β,γ-unsaturated carboxylic acids.

Furthermore, this carboxylation was applicable to mono- or 1,3-disubstituted allenes. Although slight modification of reaction conditions was required,[20] alkyl- or Ph-substituted allenes **5a**, **5b**, and 1,3-disubstituted allene **5c** reacted smoothly to give α-substituted β,γ-unsaturated carboxylic acids **6a−c** as a major product in reasonable yield in the presence of 1−2.5 mol% of **1** and 150 mol% of $ZnEt_2$ at 60 °C (Table 2). Interestingly, careful analysis revealed

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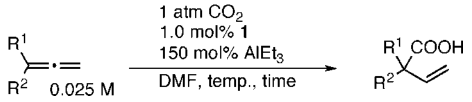
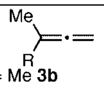
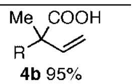
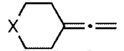
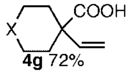
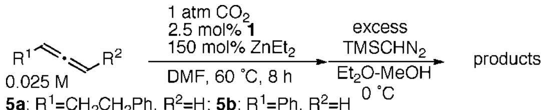
Table 1. Generality of 1,1-Disubstituted Allenes



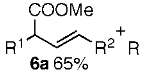
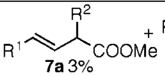
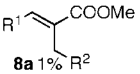
entry	allene	conditions	products
			
1	R= Me **3b**	rt, 48 h	**4b** 95%
2[a]	R= Ph **3c**	rt, 24 h	**4c** 73%
3	R= $-(CH_2)_3OTBDPS$ **3d**	50 °C, 12 h	**4d** 94%
4	R= $-(CH_2)_3OBz$ **3e**	50 °C, 12 h	**4e** quant.
5	R= $-(CH_2)_2CH{=}CMe_2$ **3f**	rt, 24 h	**4f** 85%
			
6	X= $-(CH_2)_2-$ **3g**	rt, 24 h	**4g** 72%
7	X= NBoc **3h**	50 °C, 8 h	**4h** 75%
8	X= $C(OCH_2)_2$ **3i**	rt, 48 h	**4i** 89%
9	X= C=O **3j**	rt, 48 h	**4j** 63%
10	X= CHPh **3k**	rt, 24 h	**4k**[b,c] 84%

[a] 2.5 mol% of **1** was employed. [b] dr = 91:9. [c] Isolated as its methyl ester after treatment with $TMSCHN_2$.

Table 2. Carboxylation of Mono- or Disubstituted Allenes



5a: $R^1=CH_2CH_2Ph$, $R^2=H$; **5b**: $R^1=Ph$, $R^2=H$
5c: $R^1=CH_2CH_2Ph$, $R^2=CH_2CH_2Ph$

entry	allene	products		
				
1[a]	**5a**	**6a** 65%	**7a** 3%	**8a** 1%
2[b]	**5b**	**6b** 54%	**7b** 2%	**8b** 7%
3	**5c**	**6c** (**7c**) 51%		**8c**[c] 6%

[a] 1.0 mol% of **1** was employed. [b] Yields were determined as carboxylic acid without esterification. [c] *E*/*Z* = 69:31.

that a small amount of γ-substituted β,γ-unsaturated carboxylic acids **7** and α,β-unsaturated acids **8** were obtained, which were regioisomers in the carboxylation and hydrometalation step, respectively.

In conclusion, we have developed a novel catalytic hydrocarboxylation of allenes by utilizing a silyl pincer-type palladium complex as the catalyst. This protocol is highly attractive not only as a CO_2-fixation reaction but also as a methodology for the synthesis of β,γ-unsaturated carboxylic acids due to its wide generality and high efficiency. Detailed mechanistic studies and application of this catalysis to other substrates are ongoing in our group.

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Supporting Information Available: Preparative methods and spectral and analytical data of compounds **1**−**8** and ORTEP diagram and a CIF file for **1**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(10) Allyl palladium complexes bearing *PCP*-pincer ligand are reported to act as nucleophilic allylation catalyst; see: Szabó, K. J. *Synlett* **2006**, 811.

(11) See ref 9 and references cited therein.

(12) Oligomerization of allene was often observed as a side reaction; see ref 7e.

(13) **1** was synthesized in good yield by ligand exchange of ClPd(*PSiP*) **2** with AgOTf. The structure of **1** was confirmed by X-ray analysis. For detailed procedure and ORTEP diagram, see Supporting Information.

(14) Turculet and co-workers reported preparation of **2** during this research was in progress; see ref 9c.

(15) Other solvents such as toluene, 1,4-dioxane, and THF resulted in lower conversion under the same conditions.

(16) **2** did not show catalytic activity under the same conditions probably due to its lower activity for initial transmetalation with $AlEt_3$.

(17) Other reducing agents such as Et_3SiH and BEt_3 did not afford the product.

(18) The possibility that the carboxylation occurs not with **D** but with an allylaluminum intermediate generated by metal exchange should be considered. However, the reaction in Scheme 2 just without CO_2 afforded only 9% of 3-methyl-5-phenyl-1-pentene, and 78% of **3a** was recovered. Even when the same reaction was run in the presence of diethylaluminum carboxylate, nearly the same result was obtained. These results strongly suggest that the exchange of allylpalladium to allylaluminum did not occur to an appreciable amount under the present reaction conditions and carboxylation occurs mainly with the allylpalladium intermediate.

(19) The stereochemistry was not determined.

(20) The use of $AlEt_3$ caused isomerization of the product to α,β-unsaturated carboxylic acid.

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