Direct Hydrogenation of Carboxylic Acids to Corresponding Aldehydes Catalyzed by Palladium Complexes in the Presence of Pivalic Anhydride

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Carboxylic acids are catalytically hydrogenated into corresponding aldehydes by palladium complexes in the presence of pivalic (trimethylacetic) anhydride under H_2. Less hindered aliphatic and aromatic acids are reduced to aldehydes in high yields. The method is also applicable to hydrogenation of dibasic carboxylic acids and carboxylic acids containing heterocyclic groups.

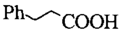
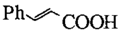
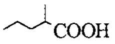
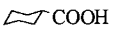
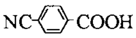
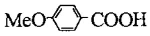
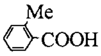
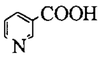
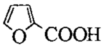
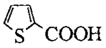
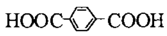
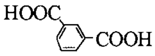
Despite the importance of aldehydes in commercial and laboratory scale organic synthesis, convenient and economical routes to aldehydes are still limited. We report here convenient one-pot synthesis of aliphatic and aromatic aldehydes catalyzed by palladium complexes. We have previously reported that palladium(0) complexes cleave the C-O bond of anhydrides to give acyl(carboxylato)palladium complexes, which react readily with atmospheric dihydrogen to release aldehydes and carboxylic acids. On the basis of the finding, a catalytic process of converting acyclic anhydrides into aldehydes and carboxylic acids in quantitative yields was developed.[1,2]

If direct hydrogenation of carboxylic acids to aldehydes can be achieved, the process would provide quite useful means in organic synthesis. We reasoned that a mixed anhydride can be generated in situ by mixing a carboxylic acid with an anhydride and the mixed anhydride can be subjected to the catalytic hydrogenation with a palladium complex to produce an aldehyde and a carboxylic acid.[3] The idea led to a new type of one-pot hydrogenation of carboxylic acids to corresponding aldehydes catalyzed by palladium complexes as reported herein.

$$\underset{\mathbf{1}}{\mathrm{RCOOH}} + \mathrm{H_2}\ (3.0\ \mathrm{MPa}) \xrightarrow[(^t\mathrm{BuCO})_2\mathrm{O}\ \mathbf{2}]{\text{Pd catalyst}} \underset{\mathbf{3}}{\mathrm{RCHO}} + \underset{\mathbf{4}}{{}^t\mathrm{BuCHO}} + \underset{\mathbf{5}}{{}^t\mathrm{BuCOOH}}$$

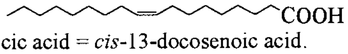
Typical procedure is as follows: a mixture of $Pd(PPh_3)_4$ (0.02 mmol), THF (5 cm^3), carboxylic acid (2 mmol, monobasic) and pivalic anhydride (6 mmol) was placed in a 100 cm^3 stainless autoclave purged with argon. The autoclave was pressurized with dihydrogen (3.0 MPa at room temperature) and the mixture was stirred at 80 °C for 24 h. The products were analyzed by GC-MS and ^1H NMR. The results of the hydrogenation are shown in the table. A variety of carboxylic acids were quantitatively hydrogenated into aldehydes. Oleic and erucic acids were converted into respective aldehydes without hydrogenation of the internal double bonds (run 4, 5) as determined by ^1H NMR. Cinnamic acid was hydrogenated poorly to give cinnamaldehyde (30%) when $Pd(PPh_3)_4$ was used as a catalyst, whereas selective formation of cinnamaldehyde in a high yield was achieved by using a $Pd(OAc)_2/2PPh_3$ catalyst

Table 1. Catalytic hydrogenation of various carboxylic acids[a]

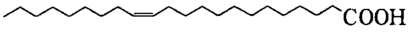
Run	Carboxylic acids	Reactants remained[b]/%		Yields[b]/%			Other products
		1[c]	**2**[c]	**3**[d]	**4**[d]	**5**[c]	
1	$^nC_7H_{15}COOH$	0	148	98	23	260	
2[e]	$^nC_7H_{15}COOH$	0	39	90	7	202	$(^nC_7H_{15}CO)_2O$[f]
3		0	154	99	25	282	
4	oleic acid[m]	0	142	99[g]	26	290	
5	erucic acid[n]	0	154	96[g]	21	276	
6[h]		-[l]	190	84	>1	184	
7		-[l]	147	64	39	227	
8		-[l]	167	63	26	292	
9	$Ph_2CHCOOH$	0	156	13	21	269	Ph_2CH_2[f] 17%[c]
10[i]	$HOOC(CH_2)_{10}COOH$	0	146	99[k]	24	272	
11	PhCOOH	tr	142	91	31	260	$(PhCO)_2O$[f] 5%[c]
12		0	143	99	26	269	
13[j]		0	126	95	38	269	
14[j]		-[l]	187	30	20	202	
15		0	126	99	53	269	
16[j]		0	140	87	42	245	
17[j]		0	145	72	55	271	
18[i]		0	161	99[k]	18	233	
19[i]		0	169	94[k]	13	230	

[a] Typical conditions are shown in the text. [b] Yields are based on the starting carboxylic acids. [c] Determined by GLC using $^nC_{17}H_{36}$ as internal standard (injection temp. 280 °C). [d] Determined by ^1H NMR using $(CHCl_2)_2$ as internal standard. [e] $(^tBuCO)_2O$, 3 mmol. [f] Detected by GC-MS. [g] Internal olefin was not hydrogenated as confirmed by ^1H NMR. [h] $Pd(OAc)_2$+2PPh_3 was used as a catalyst. [i] Carboxylic acid, 1 mmol. [j] Reaction time, 48 h. [k] Dialdehyde yield. [l] The amount of reactant remained was not determined.

[m] Oleic acid = *cis*-9-octadecenoic acid.



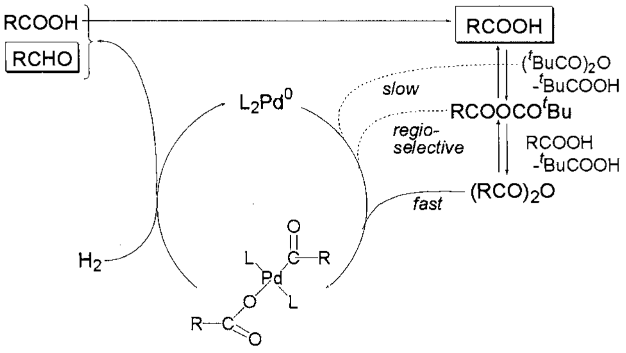
[n] Erucic acid = *cis*-13-docosenoic acid.



(run 6).

The yields of aldehydes were decreased when a more hindered carboxylic acid (run 7-9) was used, presumably due to the larger steric hindrance around the carbonyl carbon. Hydrogenation of diphenylacetic acid (run 9) gave a poor yield of the corresponding aldehyde and diphenylmethane was obtained as a major product. The result suggests occurrence of the decarbonylation of an acylpalladium intermediate to an alkylpalladium complex and its subsequent hydrogenolysis to diphenylmethane.[4]

Aromatic carboxylic acids having a *para* substituent (run 11-13) were also converted into the corresponding aldehydes in high yields. Presence of an *ortho*-substituent in the phenyl ring of benzoic acid caused considerable hindrance on the hydrogenation (run 14). Pyridinecarboxylic acid was hydrogenated into pyridinecarbaldehyde only when the carboxy group is substituted at β-position (run 15). Furancarboxylic acid and thiophenecarboxylic acid were also reduced in moderate yields (run 16, 17). Employment of terephthalic acid and isophthalic acid in this hydrogenation reaction gave terephthalaldehyde and isophthalaldehyde, respectively (run 18, 19).



Scheme 1. Proposed reaction mechanism.

The proposed reaction mechanism is as follows. The prior equilibrium of the exchange reaction between the carboxylic acid (RCOOH) and pivalic anhydride [(^{t}BuCO)$_2$O] is achieved in the reaction media to form the mixture of the three anhydrides, (RCOOCO^{t}Bu), (RCO)$_2$O and (^{t}BuCO)$_2$O. The palladium(0) complex will attack the less bulky carboxy carbon preferentially to form an acyl(carboxylato)palladium intermediate. Hydrogenolysis of the intermediate affords the corresponding aldehyde and acid as shown in our previous study on the reaction of an isolated acyl(carboxylato)palladium with dihydrogen. The carboxylic acid generated there will be converted into the mixed anhydride to be hydrogenated again.

Limited amounts of pivalaldehyde are generated in all runs due to occurrence of the hydrogenolysis of pivalic anhydride by the palladium complex.

Since the useful methodology to convert carboxylic acids into aldehydes is quite limited,[5,6] the present method provides a convenient general route to selective production of aldehydes under mild and simple conditions. We have also confirmed that heterogeneous metal catalysts such as Pd/C can also catalyze this type of hydrogenation. Further investigation is now under way.

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References and Notes

1 K. Nagayama, F. Kawataka, M. Sakamoto, I. Shimizu, and A. Yamamoto, *Chem. Lett.*, **1995**, 367.

2 Conversion of anhydrides into aldehydes and carboxylic acids catalyzed by $Co_2(CO)_8$ has been reported; H. Wakamatsu, J. Furukawa, and N. Yamakami, *Bull. Chem. Soc. Jpn.*, **44**, 288 (1971); stoichiometric formation of aldehydes in the reaction of $Na_2Fe(CO)_4$ with acid anhydrides under H_2 has been reported: Y. Watanabe, M. Yamashita, T. Mitsudo, M. Igami, and Y. Takegami, *Bull. Chem. Soc. Jpn.*, **48**, 2490 (1975).

3 In reactions of carboxylic acids with acetic anhydride in the presence of rhodium and palladium complexes, Miller et al found conversion of carboxylic acids to olefins of one less carbon atom; J. A. Miller, J. A. Nelson, and M. P. Byrne, *J. Org. Chem.*, **58**, 18 (1993).

4 Similar decarbonylation of diphenylacetyl chloride in the Rosenmund reaction conditions has been reported; J. G. Burr Jr., *J. Am. Chem. Soc.*, **73**, 3502 (1951).

5 T. Yokoyama, T. Setoyama, N. Fujita, M. Nakajima, and T. Maki, *Appl. Catal. A*, **88**, 149 (1992).

6 "Comprehensive Organic Synthesis," ed by B. M. Trost, Pergamon, Oxford (1991), Vol. 8, pp. 259-305.