ELSEVIER

Journal of Molecular Catalysis A: Chemical 157 (2000) 117–122

JOURNAL OF MOLECULAR CATALYSIS A: CHEMICAL

www.elsevier.com/locate/molcata

Regioselective hydroesterification of 1-alkynes catalyzed by palladium–phosphine complexes

M. Akao, S. Sugawara, K. Amino, Y. Inoue *

Department of Materials Chemistry, Graduate School of Engineering, Tohoku University, Aoba-ku, Sendai 980-8579, Japan

Received 2 December 1999; accepted 26 December 1999

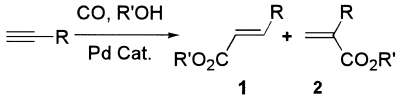
Abstract

The reaction of 1-alkynes, CO, and methanol (hydroesterification) catalyzed by palladium–phosphine complexes has been studied in acetonitrile media. Branched α,β-unsaturated ester was mainly produced in the presence of a catalytic amount of a palladium complex containing PPh_3. In contrast, dppf-based palladium complexes showed excellent regioselectivity for the formation of linear α,β-unsaturated ester. On the other hand, hydroesterification of 1,7-octadiyne with a catalyst system of $Pd(OAc)_2/PPh_3$/TsOH followed a different path to give a cyclized carbonylation product as the major product. A tentative mechanism involving a Pd−H species has been proposed for these reactions.

Keywords: 1-Alkyne; Hydroesterification; Palladium complex

1. Introduction

Palladium-catalyzed hydroesterification of 1-alkynes normally gives rise to linear and branched α,β-unsaturated esters, **1** and **2**, respectively, the ratio of which depends on the reaction conditions employed. Usually, the regioselectivity for the formation of branched ester **2** has been observed.



For example, the palladium black/HI system catalyzes the hydroesterification of phenylacetylene and propyne to afford branched esters **2** selectively [1]. Similarly, the hydroesterification of 1-alkynes catalyzed by $Pd(dba)_2$/dppb [1] gives branched ester **2** regioselectively (dba = dibenzylideneacetone) [2]. The reaction occurs well even for tertiary alcohols. Aryl- and alkylacetylenes are carbonylated even under the normal pressure of CO in the presence of $Pd(PPh_3)_4$ or $Pd(OAc)_2$/dppf using phenols as nucleophile to give branched ester **2** in good selectivity and yield [3]. Hydroesterification of 1-alkynes with butanol by the catalyst system of $Pd(dba)_2/PPh_3$/TsOH (TsOH = *p*-toluenesulfonic acid) also proceeds smoothly under the normal pressure of CO to afford branched ester **2** selectively [4]. Regioselective hydroesterification of alkynes and alkynols using formate esters cat-

* Corresponding author. Tel.: +81-22-217-5873; fax: +81-22-263-9834.

E-mail address: inoue@aporg.che.tohoku.ac.jp (Y. Inoue).

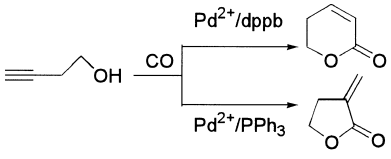
[1] Abbreviation of phosphine appears in Table 1.

1381-1169/00/$ - see front matter
PII: S1381-1169(00)00053-4

alyzed by $Pd(OAc)_2$/dppb/PPh_3/TsOH has been reported [5]. $Pd(OAc)_2$ in combination with 2-pyridyldiphenylphosphine (PPh_2Py) and $MeSO_3H$ gives a very active system which catalyzes the hydroesterification of propyne with selectivity for **2** as high as 99.95% [6]. It is suggested that the PPh_2Py ligand plays a crucial role. Recently, an investigation on the mechanism of this catalytic reaction has been reported [7].

On the other hand, catalytic systems to afford linear ester **1** selectively are scant. For instance, Knifton [8] reported the monophosphine-stabilized Pd(II)/Sn(II) system which effects the hydroesterification of 1-heptyne at 80°C and 240 atm with 81% selectivity for the linear ester **1** (65% total carbonylation yield). A somewhat different system for the production of **1** has also been reported. Thus, $Pd(dba)_2$/dppb can catalyze the regioselective conversion of 1-alkynes and formate esters to linear α,β-unsaturated esters **1** at 100°C under the CO pressure of 80 atm [9].

We have recently reported the cationic palladium-complex-catalyzed cyclocarbonylation of 3-butyn-1-ol demonstrating that Pd/dppb complex gives mainly the six-membered ring lactone, whereas Pd/PPh_3 complex selectively affords the five-membered ring one [10]. These observations suggest that a palladium complex containing dppb or other diphosphine ligand might generally catalyze the regioselective hydroesterification of 1-alkynes to linear α,β-unsaturated esters **1**, since six-membered ring lactone occurs by ensuring CO addition to the terminal carbon of the acetylenic bond:



In this paper, we report the regioselective hydroesterification of 1-alkynes catalyzed by diphosphine–palladium complexes to afford linear α,β-unsaturated esters.

2. Results and discussion

At first, cationic palladium–phosphine complexes were used as catalyst for hydroesterification because they were found to be effective in the related cyclocarbonylation reaction of 3-butyn-1-ol (vide supra). The results with 1-octyne are given in Table 1. When this acetylene was allowed to react with CO (40 atm) and methanol in acetonitrile at 120°C in the presence of catalytic amounts of PPh_3-coordinated cationic complex $[Pd(PPh_3)_2(PhCN)_2](BF_4)_2$, two regioisomeric products, methyl (*E*)-2-nonenoate (**1a**) and methyl 2-hexyl-2-propenoate (**2a**), were obtained in a combined modest yield of 12%, the branched ester **2a** being the major component (entry 1). However, repetition of the reaction with the dppe-coordinated cationic complex $[Pd(dppe)(PhCN)_2](BF_4)_2$ produced the linear ester **1a** as the major product in a combined yield of 5% (entry 2). The inversion of regioselectivity was also observed with the cationic complexes containing other bidentate phosphines, i.e., dppp (entry 3), dppb (entry 5), binap (entry 6), tol-binap (entry 7), and dppf (entry 8). With these complexes, improvement in both total yield and regioselectivity for linear ester **1a** were attained. Among them, the dppf complex seemed promising in terms of selectivity and yield. Performance of the reactions in neat methanol mostly improved the total yield of the esters by sacrificing the selectivity for **1a** as is represented by the cationic Pd/dppp complex catalyst (entries 3, 4). Other solvents such as toluene, *N*,*N*-dimethylformamide, CH_2Cl_2 and THF were inferior to acetonitrile in terms of yield and selectivity for **1a**. The reaction conditions of 120°C and 5 h seemed too severe because the starting material was consumed in competing side reactions, e.g., oligomerization. Optimization of the reaction was then studied

Table 1
Hydroesterification of 1-octyne by palladium complexes[a]

Entry	Pd complex	Bite angle (°)[b]	Pressure (atm)	Temperature (°C)	Time (h)	Yield (%)	**1a**:**2a**
1	$[Pd(PPh_3)_2(PhCN)_2](BF_4)_2$		40	120	5	12	16:84
2	$[Pd(dppe)(PhCN)_2](BF_4)_2$	85	40	120	5	5	60:40
3	$[Pd(dppp)(PhCN)_2](BF_4)_2$	91	40	120	5	27	78:22
4[c]	$[Pd(dppp)(PhCN)_2](BF_4)_2$		20	100	6	45	66:34
5	$[Pd(dppb)(PhCN)_2](BF_4)_2$	98	40	120	5	13	84:16
6	$[Pd(binap)(PhCN)_2](BF_4)_2$	92	40	120	5	44	76:24
7	$[Pd(tol\text{-}binap)(PhCN)_2](BF_4)_2$		40	120	5	31	90:10
8	$[Pd(dppf)(PhCN)_2](BF_4)_2$	96	40	120	5	37	89:11
9	$[Pd(dppf)(PhCN)_2](BF_4)_2$		40	80	2	52	90:10
10	$[Pd(dppf)(PhCN)_2](BF_4)_2$		60	80	2	85	86:14
11	$[Pd(dppf)(PhCN)_2](BF_4)_2$		60	80	3	quant.	85:15
12	$PdCl_2(dppf)$		60	80	3	quant.	92:8

[a]1-Octyne 2 mmol, Pd complex 0.04 mmol, MeOH 3 ml, MeCN 10 ml.
[b]Bite angle of diphosphine is quoted from Ref. [14]. dppe = $Ph_2P(CH_2)_2PPh_2$, dppp = $Ph_2P(CH_2)_3PPh_2$, dppb = $Ph_2P(CH_2)_4PPh_2$, binap = 2,2′-bis(diphenylphosphino)-1,1′-binaphthyl, tol-binap = 2,2′-bis(di(p-tolyl)phosphino)-1,1′-binaphthyl, dppf = 1,1′-bis(diphenylphosphino)ferrocene.
[c]1-Octyne 2.5 mmol, Pd complex 0.05 mmol, MeOH 5 ml.

by changing the reaction conditions. Thus, employment of lower reaction temperature of 80°C (entry 8) increased pressure of 60 atm (entry 9), and shorter reaction time (entries 8–10) provided the esters in a quantitative yield without losing the high selectivity for **1a** (entry 10). As a control experiment, we employed a neutral complex, $PdCl_2$(dppf), as catalyst and were pleased to find that it is equally efficient for the hydroesterification, providing the esters **1a** and **2a** in a quantitative yield with excellent selectivity for the linear ester **1a** of 92% (entry 11).

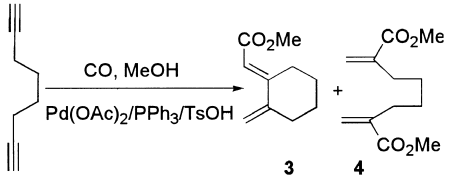
Table 2 shows the results of hydroesterification of other 1-alkynes. The reaction of phenylacetylene with CO catalyzed by the cationic Pd/dppp complex in methanol solvent produced the branched ester, methyl 2-phenyl-propenoate (**2b**), as the major product (entry 1). In contrast, the linear ester, methyl (*E*)-3-phenyl-2-propenoate (**1b**), was produced preferentially

Table 2
Hydroesterification of 1-alkynes catalyzed by palladium complexes[a]

Entry	1-Alkyne	Palladium complex	Temperature (°C)	Time (h)	Yield (%)		**1**:**2**
1[b]	HC≡CPh	$[Pd(dppp)(PhCN)_2](BF_4)_2$	100	6	77	**1b2b**	44:56
2		$[Pd(dppp)(PhCN)_2](BF_4)_2$	120	5	76		82:18
3		$[Pd(dppb)(PhCN)_2](BF_4)_2$	120	5	35		81:19
4		$[Pd(dppf)(PhCN)_2](BF_4)_2$	120	5	75		89:11
5		$[Pd(dppf)(PhCN)_2](BF_4)_2$	80	2	71		89:11
6		$PdCl_2(dppf)$	80	2	41		87:13
7	HC≡CTMS	$[Pd(dppf)(PhCN)_2](BF_4)_2$	80	2	29	**1c2c**	100:0
8	$HC{\equiv}CCO_2Me$	$[Pd(dppf)(PhCN)_2](BF_4)_2$	80	2	40	**1d2d**[c]	55:45

[a]1-Alkyne 2 mmol, Pd complex 0.04 mmol, CO 40 atm, MeOH 3 ml, MeCN 10 ml.
[b]Phenylacetylene 2.5 mmol, Pd complex 0.05 mmol, CO 20 atm, MeOH 5 ml.
[c]**2d**;Methanol adduct $MeOCH_2CH(CO_2Me)_2$.

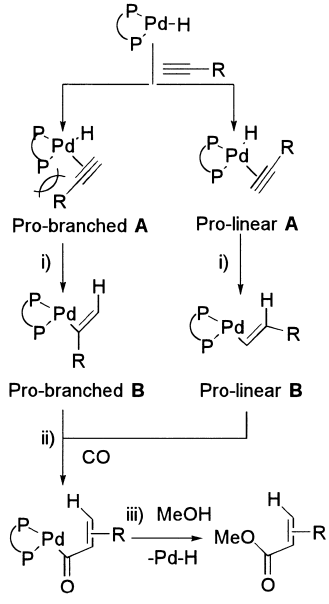
with the same palladium complex in acetonitrile solvent (entry 2). Other palladium complexes coordinated with dppb, and dppf also catalyzed the hydroesterification of phenylacetylene to produce the linear ester **1b** preferentially in moderate to reasonable yields (entries 3–6). The results with phenylacetylene are remarkable because this acetylene is reported to be a substrate with distinct preference for the formation of the branched products on the palladium-catalyzed hydroesterification [8] and hydrocarboxylation [11]. Hydroesterification of bulky trimethylsilyl (TMS) group-substituted acetylene catalyzed by the cationic Pd/dppf complex demonstrated the complete selectivity for the linear ester **1c** (R = TMS) albeit in modest yield (entry 7). On the other hand, the linear/branch ratio of the product with the methoxycarbonyl-group-substituted acetylene was 55:45, slightly in favor of the linear ester **1d** ($R = CO_2Me$) (entry 8).



Then we attempted the hydroesterification of α,ω-diyne. When 1,7-octadiyne was allowed to react with CO (10 atm) and methanol in acetonitrile at 80°C in the presence of $[Pd(dppe)(PhCN)_2](BF_4)_2$, $[Pd(dppp)(PhCN)_2](BF_4)_2$, or $[Pd(dppb)(PhCN)_2](BF_4)_2$ complex, almost no carbonylation products were obtained unfortunately. Instead, we observed the formation of a small amount of a cyclized carbonylation product, methyl (*E*)-2-methylenecyclohexylidenemethanoate (**3**), under the catalysis with $[Pd(PPh_3)_2(PhCN)_2](BF_4)_2$. This finding prompted a study of using the monophosphine ligand, PPh_3. After intensive studies, we found that $Pd(OAc)_2/PPh_3$/TsOH catalytic system produces the cyclized product **3** in an increased yield of 45% together with the non-cyclized di-ester dimethyl 2,7-dimethyleneoctanedioate (**4**) in 13% yield after 16 h reaction at 80°C under the CO pressure of 5 atm. Non-cyclized mono-ester was produced in considerably smaller amounts than **4**. The reaction did not take place in the absence of TsOH. Increasing CO pressure to 20 atm or replacing $Pd(OAc)_2$ with $PdCl_2$ resulted in the formation of the non-cyclized di-ester **4** as the major product. Only one precedent has been reported so far for this type of cyclized carbonylation reaction where pyrrolidine derivatives containing an exocyclic carbonyl group have been obtained by the reaction of tetraalkyl-substituted dipropargylamines with CO and alcohols in the presence of PdX_2/thiourea as catalyst (X = Cl,Br,I) [12].

In principle, two mechanisms have been presented for the palladium-catalyzed hydroesterification of alkynes. The first is the hydride mechanism involving a Pd–H species and the second is the alkoxycarbonyl mechanism involving a $Pd–CO_2R$ species. We tentatively propose the hydride mechanism for this reaction as is shown in Scheme 1.

This involves (i) insertion of the coordinated alkyne into a Pd–H bond to give a (σ-vinyl)palladium complex; (ii) CO insertion into the Pd–C



Scheme 1.

bond to afford an acylpalladium complex; (iii) methanolysis of the acyl complex to yield the ester, regenerating the hydride. The regiochemistry of hydroesterification is determined in step (i). Naturally, steric and electronic factors of diphosphine ligand influence the regioselectivity. Since all the diphosphine ligands tested in this study have diphenylphosphino or di(*p*-tolyl)phosphino group, the difference in electronic factors may be minimized. A literature precedent describes that the regiochemistry can be attributed mainly to steric effects [11]. Thus, the Pd–H bond tends to add preferentially to the less crowded carbon, i.e., to the terminus via the pro-branched intermediate A, giving rise to the pro-branched intermediate B. In this case, however, the addition of Pd–H to the terminal carbon of 1-alkynes would place the substituent R closer to the ligand in the pro-branched intermediate A. For chelating diphosphine ligands, this interaction would increase because of the backbone constrains. The interaction will further increase with the backbone rigidity and the bite angle of the diphosphine ligand. In such circumstances, the pro-linear intermediate A rather than the pro-branched intermediate A may be relatively stable where the direction of coordinated 1-alkyne is opposite.

The importance of substrate–ligand interaction on regioselectivity is actually demonstrated in the reactions catalyzed by the complexes coordinated by binap and tol-binap ligands (entries 5, 6 in Table 1). These ligands have the same backbone of binaphthyl and are only different in the substituents on the phosphorus atom: one is phenyl and the other is bulkier *p*-tolyl. They are expected to have almost the same bite angle and electronic properties. The results of the hydroesterification with these complexes showed that the linear/branch ratio of the product increased when binap was replaced by tol-binap. Thus, the larger the steric interactions between substrate and ligand, the larger the linear/branch ratio of the product. Among the diphosphines employed, dppf demonstrated good selectivity for linear ester. This can be rationalized by the wide bite angle (Table 1) and by the rigid ferrocenyl backbone of the diphosphine.

The formation of cyclized carbonylation product **3** can be explained by assuming (i) addition of Pd–H to the terminus of the diyne; (ii) internal insertion of another triple bond into the resulting Pd–C bond to give a six-membered ring intermediate; and (iii) insertion of CO followed by methanolysis.

3. Experimental

3.1. Materials

Alkynes (1-octyne, phenylacetylene, trimethylsilylacetylene, methyl propiolate, and 1,7-octadiyne) and diphosphines (dppe, dppp, dppb, and dppf) were obtained commercially. Binap and tol-binap were kindly donated from Takasago International. The cationic palladium complexes were prepared by treatment of the corresponding dichloro complexes with $AgBF_4$ according to the literature method [13].

3.2. General procedure for hydroesterification of 1-alkynes

Into a 50-ml stainless steel autoclave, 1-alkyne (2 mmol), palladium complex (0.04 mmol), methanol (74 mmol; 3 ml), and acetonitrile (10 ml) were charged under N_2 atmosphere. Then CO was introduced up to 40 atm. The autoclave was then heated in an oil bath (80–120°C) with stirring. After the reaction, the reaction mixture was passed through a short SiO_2 column eluting with diethyl ether to remove palladium complexes. Then the solvent was evaporated and the residue was subjected to column chromatography on SiO_2 (**1d**) eluting with hexane/ethyl acetate (**1d**) or Kugelrohr distillation (**2d**) followed by preparative GLC (**1a**, **2a**, **1b**, **2b**, **1c**, **3**, **4**) to isolate the products. The products were identified by a combination of GLC, IR, ^1H and ^{13}C NMR, mass, and elemental analysis techniques.

3.3. Hydroesterification of 1,7-octadiyne

Into a 50-ml stainless steel autoclave, 1,7-octadiyne (2 mmol), $Pd(OAc)_2$ (0.1 mmol), PPh_3 (0.2 mmol), TsOH (0.5 mmol), MeOH (74 mmol; 3 ml), and acetonitrile (30 ml) were charged under N_2 atmosphere. Then CO was introduced up to 5 atm. The autoclave was heated in an oil bath at 80°C for 16 h. After the reaction, the mixture was taken up in diethyl ether (20 ml) and washed with 1 M NaCl three times. The organic layer was dried ($MgSO_4$), filtered, and concentrated to give the crude products, which were chromatographed on SiO_2 (hexane/ethyl acetate = 5) followed by Kugelrohr distillation (100°C/2 mmHg). The products were then subjected to preparative GLC to obtain the analytical samples.

3.4. **3**

Oil. IR (neat): 1719, 1634, 1191 cm^{-1}. ^1H NMR ($CDCl_3$): δ 5.86 (s, 1H, $=CHCO_2Me$), 5.01 (d, $J = 1.1$ Hz, 1H, $=CHH$, proximal to the other C=C), 4.79 (d, $J = 1.1$ Hz, 1H, $=CHH$, distal to the other C=C), 3.73 (s, 3H, Me), 2.98–2.93 (m, 2H, $CH_2C=CCO_2Me$), 2.38–2.33 (m, 2H, $CH_2C=CH_2$), 1.75–1.67 (m, 4H, $-CH_2CH_2-$). ^{13}C NMR ($CDCl_3$): δ 167.2, 161.2, 149.6, 112.5, 110.7, 50.9, 35.4, 29.8, 26.5, 25.0. GC mass (70 eV): *m/e* 39 (89), 79 (78), 91 (100), 107 (67), 138 (65), 166 (89, M^+). The *E* stereochemistry around the double bond was determined by NOE experiments.

3.5. **4**

Oil. IR (neat): 1720, 1634, 1192 cm^{-1}. ^1H NMR ($CDCl_3$): δ 6.14 (s, 2H, $HHC=CCO_2Me$, *cis* to CO_2Me), 5.53 (s, 2H, $HHC=CCO_2Me$, *trans* to CO_2Me), 3.75 (s, 6H, Me), 2.24–2.23 (m, 4H, $CH_2C=C$), 1.52–1.47 (m, 4H, $-CH_2CH_2-$). ^{13}C NMR ($CDCl_3$): δ 167.7, 140.3, 124.8, 51.8, 31.7, 27.9. GC mass (70 eV): *m/e* 41 (94), 53 (53), 67 (100), 79 (45), 95 (50), 107 (83), 194 (6, M^+).

References

[1] K. Mori, T. Mizoroki, A. Ozaki, Chem. Lett. (1975) 39.
[2] E. Ali, H. Alper, J. Mol. Catal. 67 (1991) 29.
[3] K. Itoh, M. Miura, M. Nomura, Tetrahedron Lett. 33 (1992) 5369.
[4] Y. Kushino, K. Itoh, M. Miura, M. Nomura, J. Mol. Catal 89 (1994) 151.
[5] E. Ali, H. Alper, J. Mol. Catal. 96 (1995) 197.
[6] A. Drent, M. Budzelaar, J. Organomet. Chem. 455 (1993) 247.
[7] A. Scrivanti, V. Beghetto, E. Campagna, M. Zanato, U. Matteoli, Organometallics 17 (1998) 630.
[8] F. Knifton, J. Mol. Catal. 2 (1977) 293.
[9] H. Alper, M.S. Maldonado, I.J.B. Lin, J. Mol. Catal. 49 (1988) L27.
[10] K. Tezuka, Y. Ishizaki, Y. Inoue, J. Mol. Catal. A: Chem. 129 (1998) 199.
[11] D. Zargarian, H. Alper, Organometallics 12 (1993) 712.
[12] P. Chiusoli, M. Costa, E. Masarati, J. Organomet. Chem. 255 (1983) C35.
[13] A. Davies, A. Hartley, G. Murry, J. Chem. Soc., Dalton Trans. (1980) 2246.
[14] P. Dierkes, P.W.N.M. van Leeuwen, J. Chem. Soc., Dalton Trans. (1999) 1519.