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Highly regioselective hydroformylation of 1,5-hexadiene to linear dialdehyde catalyzed by rhodium complexes with tetraphosphorus ligands

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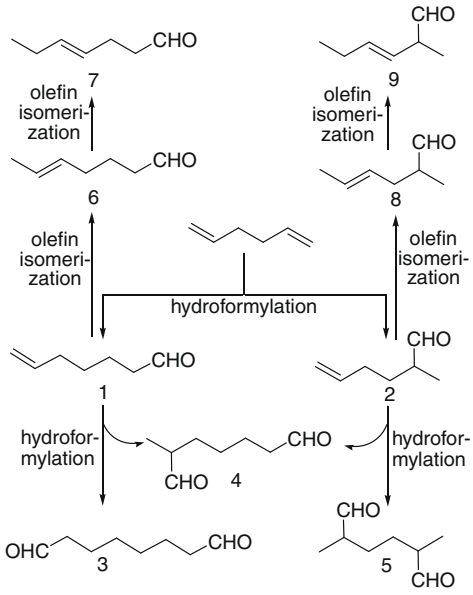
ABSTRACT

Rhodium-catalyzed hydroformylation of 1,5-hexadiene to corresponding dialdehydes was investigated using tetraphosphorus ligands. These ligands showed a high regioselectivity for linear aldehydes (linear to branch ratio up to 98%) in very good yield (up to 87%). It was found that the introduction of the substituents at the ortho position of the biphenyl moiety has little effect on the regioselectivity and the electron-donating substituents retard the reaction somewhat.

Hydroformylation of alkenes represents a highly attractive method to prepare aldehydes and alcohols, and is one of the most important reactions in industry catalyzed by homogeneous catalysts. Production is estimated over 9 million tons annually.[1] Many efforts have been devoted to the development of systems with improved regioselectivity toward the formation of the industrially more important linear aldehydes.[2] Both phosphine- and phosphite-based systems giving high regioselectivities to linear aldehydes for the hydroformylation of terminal and internal alkenes have been reported.[3] Recently, there has been increased interest in the regioselective hydroformylation of ready available functionalized alkenes.[4] One of such cheap, useful feedstock is 1,*n*-diolefins.

Double hydroformylation of 1,*n*-diolefins would produce dialdehydes, which are valuable intermediates for the preparation of a variety of commercially important products such as bicarboxylic acids and their derivatives,[5] diamines,[6] alicyclic, and heterocyclic compounds having different structures.[7] Particularly important is the use of the dialdehydes as cross-linking agents for polymers such as proteins,[8] polysaccharides,[9] and other functionalized macromolecular compounds.[10] However, only in particular cases this method appears capable to give acceptable results. In most cases, a complex mixture of monoaldehydes and dialdehydes, arising from the consequent hydroformylation–isomerization–hydroformylation of the two double bonds was obtained, which made this process less practical (1,5-hexadiene as example, Scheme 1).

In 1964 Morikawa reported some interesting results concerning the *oxo*-reaction on 1,4-pentadiene and 1,5-hexadiene: the yield of linear dialdehydes, however, did not exceed 40% and in some cases the formed pimelaldehyde is transformed in the reaction medium



Scheme 1. Hydroformylation of 1,5-hexadiene.

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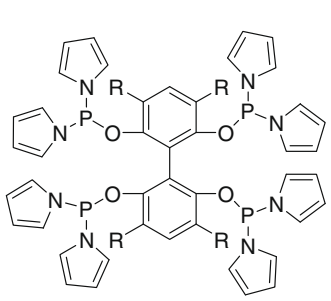

L1 R = H
L2 R = Cl
L3 R = Me
L4 R = Et
L5 R = Ph
L6 R = *p*-F-Ph
L7 R = Tolyl

Scheme 2. Ligands used in this study.

into cyclohexancarboxaldehyde through intramolecular aldol condensation.[5] Later, other groups investigated this reaction using different catalytic systems or in special reaction media.[11] The real breakthrough was made by Marchetti who found that 1,5-hexadiene could be converted to the corresponding linear dialdehydes selectively in over 80% yield when $RhH(CO)(PPh)_3$ was combined with Xanphos.[12] Other methods known to transform various functionalities into the aldehyde group, which has been successfully used for the preparation of monoaldehydes, only in a few cases can be conveniently extended to the preparation of dialdehydes. The chemoselectivities are often unsatisfactory due to the formation of other products such as cyclic lactones and other side reactions. Thus, it is highly desirable to develop new, economic, and efficient process for the synthesis of linear dialdehyde.

Recently, we have reported the synthesis and application of a class of new tetraphosphorus ligands (Scheme 2), which showed to promote an exceptionally high regioselectivity toward the formation of linear aldehydes in the rhodium-catalyzed hydroformylation of olefins.[13] The peculiar behavior of these ligands was ascribed to the large 'natural' bite angle formed by coordination with the metal (nine-member ring), the multiple coordination modes keeping the formation of the selective catalytic species in the greatest degree,[14] and the electron-withdrawing property of *N*-pyrrolylphosphorus moiety.[15] The high regioselectivity and reactivity prompted us to assess our ligands further in the hydroformylation of 1,*n*-diolefins. Herein, we wish to disclose our recent studies on the hydroformylation of 1,5-hexadiene.

Initially, 1,5-hexadiene was subjected to rhodium-catalyzed hydroformylation in toluene at 100 °C and 10 atm ($CO/H_2 = 1$) for 2 h using ligand L1 (Table 1).[16] Under this reaction condition, the starting material was almost completely consumed. A mixture of olefin isomers (formed via the isomerization of the carbon–carbon double bond of the original diolefins, 1,4-hexadiene was the main isomer), monoaldehydes (6-hepten-1-al **1** and 2-methyl-5-hexen-1-al **2**, and isomers **6**–**9** from the migration of the double bond of the original monoaldehydes **1** and **2**, **6** was the main isomer) and dialdehyde compounds (1,8-octanedial **3**, 2-methyl-1,7-heptanedial **4,** and 2,5-dimethyl-1,6-hexanedial **5**) was obtained in 14.4%, 11.5% (**1**/**2** = 96.3/3.7), 26.2%, and 47.9% (**3**/**4**/**5** = 94.1/5.3/0.6) yields, respectively. The effect of syngas pressure was then investigated. It was found that the syngas pressure has a significant influence on the yield of dialdehydes (entries 2–5). With the increased pressure from 10 ($CO/H_2 = 1$) to 80 atm ($CO/H_2 = 1$), the amounts of olefin isomers and monoaldehydes decreased steadily, along with the increasing yield of the dialdehydes (up to 87%). Meanwhile, the product distribution almost not changed under the reaction conditions used. It was also found that the decrease of temperature from 100 °C to 60 °C has little effect on the product distribution (entries 6 and 7).

Based on the optimal reaction condition for ligand L1 (100 °C, $H_2/CO = 40/40$ atm, $t = 2$ h), 1,5-hexadiene was then hydroformylated using the complex formed in situ from $Rh(acac)(CO)_2$ and L2–L7. The results are summarized in Table 2. In our previous studies, we have found that the introduction of substituents at the 3,3′,5,5′-position of the biphenyl moiety would greatly increase the regioselectivity for the linear aldehydes.[13b,c] Surprisingly, the effect of these substituents on the regioselectivities was not as remarkable as observed before. In all the cases, a high linear to branch ratio was obtained for both the monoaldehydes and the dialdehydes. This phenomenon may hint that the big natural bite instead of the steric of the biphenyl moiety controlled the regioselectivity. However, these substituents did have some effects on the yields of dialdehydes **6**–**9**, which decreased with the introducing of electron-donating groups such as Me, Et, and *p*-MePh (Table 2, entries 2–4 and 6).

In summary, we have shown that the hydroformylation of 1,5-hexadiene can be achieved with essentially high regioselectivity (linear selectivity is up to 98%) by using tetraphosphorus-based Rhodium catalyst. It was found that the introducing of the substituents at the ortho position of the biphenyl moiety has little effect on the regioselectivity and the electron-donating substituents retard the reaction somewhat. Further ligands applications and mechanism studies are now under investigation and will be reported in due course.

Table 1
Hydroformylation of 1,5-hexadiene using ligand L1 under different reaction conditions[a]

Entry	Pressure H_2/CO (atm)	Temperature (°C)	Conv.[b] (%)	Olefin isomer[c] (%)	Yield (%)		
					Monoaldehydes		Dialdehydes **3**+**4**+**5** (**3**/**4**/**5**)[f]
					1+**2** (**1**/**2**)[d]	**6**–**9**[e]	
1	5/5	100	>99	14.4	11.5(96.3/3.7)	26.2	47.9(94.1/5.3/0.6)
2	10/10	100	>99	3.3	7.4(96.8/3.4)	17.9	71.3(95.2/4.3/0.5)
3	20/20	100	>99	1.2	4.7(97.1/2.9)	13.5	80.6(96.7/2.9/0.4)
4	30/30	100	>99	<1	3.5(97.2/2.8)	8.2	87.3(97.4/2.3/0.3)
5	40/40	100	>99	<1	5.6(96.2/3.8)	6.3	87.6(97.4/2.3/0.3)
6	40/40	80	>99	<1	3.6(97.4/2.6)	8.3	87.4(97.4/2.3/0.3)
7	40/40	60	>99	<1	6.0(97.6/2.4)	6.7	86.8(97.5/2.2/0.2)

[a] S/C = 1,000, Rh/L = 4/1, [Rh] = 1.0 mM, $t = 2$ h, toluene as solvent, decane as internal standard. The oxo-products were identified by GC–mass spectroscopy. Compound **1**: MS: *m*/*z* (%) 39 (47), 41 (100), 42 (32), 43 (31), 55 (45), 67 (49), 68 (78), 79 (30). 81 (16), 86 (11), 112 (1). Compound **2**: MS: *m*/*z* (%) 41 (88), 55 (58), 57 (27), 58 (100), 112 (2). Compound **3**: MS: *m*/*z* (%) 41 (100), 42 (27), 43 (61), 44 (65), 54 (41), 55 (67), 57 (88), 80 (26), 81 (79), 98 (13), 110 (17), 142 (5). Compound **4**: MS: *m*/*z* (%) 41 (100), 43 (69), 55 (35), 57 (60), 58 (83), 69 (29), 112 (15), 124 (21), 142 (2). Compound **5**: MS: *m*/*z* (%) 41 (61), 43 (100), 55 (67), 57 (49), 58 (77), 71 (40), 84 (51), 96 (21), 124 (14), 142 (1).
[b] Conversion of 1,5-hexadiene, determined on the basis of GC.
[c] The yield of 1,5-hexadiene isomerization products, determined on the basis of GC.
[d] Determined on the basis of GC analysis.
[e] Total yield of the monoaldehydes **6**, **7**, **8,** and **9**.
[f] Determined on the basis of GC.

Table 2
Hydroformylation of 1,5-hexadiene using ligand L2–L7 under optimized pressure and temperature[a]

Entry	L	Yield (%)			
		Olefin isomer[b] (%)	Monoaldehydes		Dialdehydes **3**+**4**+**5** (**3**/**4**/**5**)[e]
			1+**2** (**1**/**2**)[c]	**6**–**9**[d]	
1	L2	<1	8.0 (96.2/3.6)	8.7	82.1 (97.5/2.2/0.3)
2	L3	<1	4.6 (96.8/3.2)	17.9	76.9 (98.1/1.7/0.2)
3	L4	<1	8.3 (95.9/4.1)	12.1	78 (98.3/1.4/0.3)
4	L5	<1	8.9 (94.9/5.1)	10.5	79.1 (97.7/2.0/0.3)
5	L6	<1	8.0 (97.4/2.6)	8.7	81.7 (96.8/2.9/0.3)
6	L7	<1	11.1 (95.0/5.0)	16.9	67.8 (96.7/3.0/0.3)

[a] S/C = 1,000, Rh/L = 4/1, [Rh] = 1.0 mM, 100 °C, H_2/CO = 40/40 atm, t = 2 h, conversion >99%, toluene as solvent, decane as internal standard.
[b–e] See Table 1.

Acknowledgments

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16. Experimental: A 2-mL vial with a magnetic stirring bar was charged with ligand L1 (4 μmol, 3.6 mg) and $Rh(acac)(CO)_2$ (1 μmol, 0.1 mL of 10 mM solution in toluene). The mixture was stirred for 5 min, 1,5-hexadiene(1.0 mmol, 0.12 mL) was then added, followed by decane (0.1 mL) as internal standard and toluene (0.68 mL). The reaction mixture was transferred to an autoclave. The autoclave was purged with nitrogen three times and subsequently charged with CO (40 atm) and H_2 (40 atm). The autoclave was then heated to 100 °C and the pressure was set to 80 atm. After 2 h, the autoclave was cooled in icy water, and the pressure was carefully released in a well-ventilated hood. The reaction mixture was immediately analyzed by GC to determine the conversion and regioselectivity.