Hydroformylation of Monoterpenic Polyenes: Effect of the Conjugation of Double Bonds on Reactivity

Humberto J. V. Barros, José G. da Silva, Cristiane C. Guimarães, Eduardo N. dos Santos, and Elena V. Gusevskaya*

Departamento de Química, Universidade Federal de Minas Gerais, 31270-901, Belo Horizonte, MG, Brazil

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Rhodium-catalyzed hydroformylation of a series of monoterpenic polyenes, i.e., myrcene (**1**), α-terpinene (**2**), γ-terpinene (**3**), terpinolene (**4**), and limonene (**5**), was studied in the presence of various monophosphines. Effects of reaction variables, such as the ligand to rhodium ratio, ligand basicity, and partial pressures of reacting gases were evaluated for each reactive substrate. The hydroformylation of conjugated olefins **1** and **2** results in two main aldehydes in each case with excellent combined selectivities and can be performed under mild conditions (80 °C, 80 atm) using a large excess of PPh_3 (P/Rh = 20−40). The hydroformylation of **1** follows the trends opposite to those usually observed with simple olefins: the increase in the concentration of the phosphorus ligand, ligand basicity, and pressure of both hydrogen and CO strongly accelerates the reaction showing that the most critical step is a conversion of η^3-allylrhodium intermediates into much more reactive η^1-complexes. The hydroformylation of **2** does not seem to occur through the formation of η^3-complexes and at low P/Rh ratios and in systems with more bulky ligands than PPh_3, such as PBz_3 and PCy_3, is strongly complicated by the hydrogenation of the substrate. Nonconjugated olefins **3** and **4** show an extremely low reactivity toward hydroformylation under similar conditions, whereas in substrate **5**, only a terminal exocyclic double bond reacts with rhodium to give a corresponding aldehyde in near quantitative yield. Thus, the endocyclic double bond in *p*-menthane dienes **2**−**5** can be hydroformylated at a reasonable rate under relatively mild conditions only if it is conjugated with another double bond. All obtained aldehydes have a pleasant scent and can be useful as components of synthetic fragrances.

Introduction

Hydroformylation represents an important entry to aldehydes and alcohols and a promising method to the valorization of various natural substrates including monoterpenic olefins, the main components of essential oils. Most oxygenated derivatives of these compounds show interesting olfactory and biological activity and can be useful in pharmaceutical and fragrance industries.[1−4] Hydroformylation of monoterpenes has been extensively discussed in the literature; however, most of the works deal with monoterpenes containing terminal exocyclic double bonds, such as limonene, β-pinene, and camphene.[4−17] Endocyclic monoterpenes, e.g., α-pinene, 2-carene, and 3-carene, are much less reactive then their exocyclic isomers; however, they can also be hydroformylated under relatively mild conditions in the presence of special ligands.[6,16,18]

On the other hand, only few reports have appeared on the hydroformylation of monoterpenes containing conjugated double bonds, such as myrcene and α-terpinene.[7,16,19−21] Most of these works report the formation of complex mixtures of products and, in the case of α-terpinene, very severe

* Corresponding author. E-mail: elena@ufmg.br.

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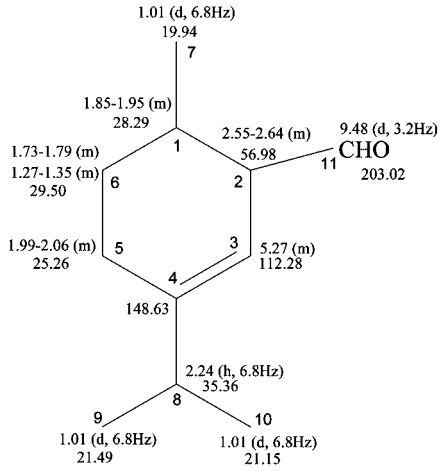
Chart 1. NMR Data for Aldehydes 9 and 10 Derived from α-Terpinene



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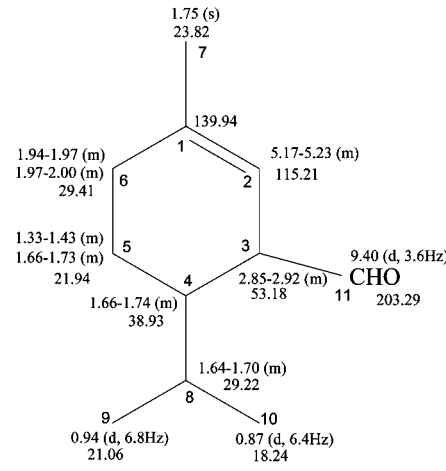

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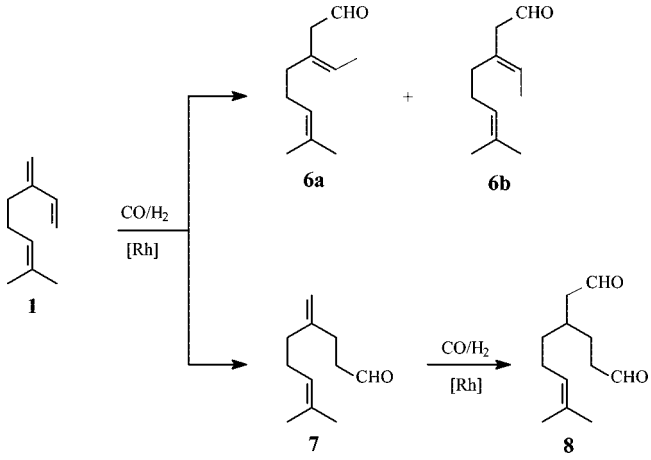
Scheme 1. Hydroformylation of Myrcene (1)



conditions (200−300 atm) applied to attain reasonable rates. For example, we have previously detected nine aldehydes at the hydroformylation of myrcene, which usually needed 24−48 h to be completed.[20]

Conjugated dienes are very resistant to hydroformylation, and probably for this reason, these reactions have attracted much less attention than hydroformylation of nonconjugated olefins. Hydroformylation of butadiene with rhodium−monophosphine catalysts usually results in a mixture of saturated and unsaturated mono- and dialdehydes and requires severe conditions (120−175 °C, 200−300 atm).[22] Rhodium/diphosphine systems operate under milder conditions and give better selectivities, but a substitution of diphosphines by triphenylphosphine virtually deactivates the catalysts.[23,24]

Such a low reactivity of conjugated dienes toward hydroformylation is attributed to the formation of stable rhodium η^3-allyl complexes which are very resistant to the insertion of CO.[20,23] Trace amounts of conjugated dienes can even slow down the hydroformylation of nonconjugated olefins because they trap rhodium catalysts in a competitive situation.[25] It is now accepted that rhodium η^3-allyls have to be converted in η^1-allyl complexes for the CO insertion to occur.[23,26−28] Recently, we have investigated the hydroformylation of isoprene as a model molecule.[28] The study of the effects of the reaction variables revealed remarkable trends, opposite to those usually observed with simple olefins. The increase in the concentration of phosphorus ligands and/or ligand basicity strongly accelerated the reaction. Moreover, the reaction showed unusual kinetics, being near first order in both hydrogen and CO pressure under "common" hydroformylation conditions. These findings allowed the hydroformylation of isoprene to be performed under mild conditions with rhodium catalysts promoted by triphenylphosphine, the most accessible, low cost, and stable phosphorus ligand employed in hydroformylation. A preliminary study showed that the method can be extended to natural monoterpenes with conjugated double bonds, i.e., myrcene.[27]

In the present work, we report the results of a comparable study on the rhodium-catalyzed hydroformylation of various monoterpenic polyolefins, i.e., myrcene, α-terpinene, γ-terpinene, terpinolene, and limonene, and discuss the effect of the conjugation of olefinic bonds on their reactivity.

Experimental Section

All chemicals were purchased from commercial sources and used as received, unless otherwise indicated. $[Rh(COD)(OAc)]_2$ was prepared by a published method with slight modifications.[29] Toluene was purified under reflux with sodium wire−benzophenone for 6 h and then distilled under argon. Myrcene was distilled before use.

Catalytic experiments were carried out in homemade autoclaves with magnetic stirring. Reactions were followed by gas chromatography (GC) using a sampling system. The products were analyzed by gas chromatography (GC-Shimadzu 17A, Carbowax 20 M capillary column, FID detector). Conversion and selectivity were determined by GC. The GC mass balance was based on the substrate charged using dodecane as an internal standard.

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In a typical run, a toluene solution (15.0 mL) containing $[Rh(COD)(OAc)]_2$ (3.7×10^{-3} mmol), phosphorus ligand (0.015−3.0 mmol), substrate (3.0 mmol), and dodecane (1.5 mmol, internal standard) was transferred under argon into a stainless steel autoclave, which was pressurized to 20−80 atm (CO/H_2 = 1/4 to 4/1), placed in an oil bath (80−100 °C), and magnetically stirred. After the reaction was carried out and cooled to room temperature, the excess CO and H_2 were slowly vented.

The products were separated by a column chromatography (silica gel 60) using mixtures of hexane and CH_2Cl_2 as eluents and identified by GC−MS, ^1H NMR, and ^{13}C NMR. The assignment of ^1H and ^{13}C NMR signals was made using bidimensional techniques. NMR spectra were recorded in $CDCl_3$ using a Bruker 400 MHz spectrometer, with TMS as an internal standard. Mass spectra were obtained on a Hewlett-Packard (5890/Series II) instrument operating at 70 eV.

Aldehydes 6a, 6b, 7, and 8. These compounds were described in our previous work.[20]

Data for Aldehyde 9. Shorter GC retention time compared to aldehyde **10**: MS (*m/z* rel int) 166/51 (M^+), 137/100 (M^+ − CHO), 95/100, 93/52, 91/60, 81/100, 79/66, 77/66, 69/69, 67/70, 55/50. For NMR data, see Chart 1.

Data for aldehyde 10: MS (*m/z* rel int) 166/14 (M^+), 137/92 (M^+ − CHO), 95/84, 93/35, 91/40, 81/100, 79/62, 77/56, 69/62, 67/46. For NMR data, see Chart 1.

Aldehyde 11. This compound was described by Kollár et al.[30]

Results and Discussion

We have studied the hydroformylation of myrcene (**1**), α-terpinene (**2**), γ-terpinene (**3**), terpinolene (**4**), and limonene (**5**) using $[Rh(COD)(OAc)]_2$ as a catalyst precursor in the presence of triphenylphosphine or other monophosphines as P-donor auxiliary ligands. Under optimized conditions, the reactions with substrates **1**, **2**, and **5** occurred relatively fast, giving one or two major carbonylated products in a 90−98% combined selectivity, whereas substrates **3** and **4** showed an extremely low reactivity toward hydroformylation. The GC mass balance was based on the substrate charged using dodecane as an internal standard. The difference, which was very small for most of the runs, was attributed to the formation of high molecular weight products, which could not be determined by GC. The products given as "others" in the tables are mainly other isomers of the substrates and unidentified aldehydes.

Hydroformylation of Myrcene. Effect of the PPh_3 Concentration. At P/Rh = 2, the hydroformylation of myrcene with Rh/PPh_3 occurs very slowly: only a 35% conversion has been observed for 22 h at 80 °C and 80 atm (Table 1, run 1). We have found that the reaction can be significantly accelerated by the increase in the PPh_3 concentration: at P/Rh = 10, a complete conversion of the substrate occurs for 13 h, at P/Rh = 20 for 8 h, and at P/Rh = 40 for only 6 h (Table 1, runs 2−4). The reaction mainly results in unsaturated aldehyde **6** and dialdehyde **8** obtained in ca. 90% combined yield, from which ca. 85% is aldehyde **6** (Scheme 1). Aldehyde **6** is formed as a mixture of two isomers: *trans* (**6a**) and *cis* (**6b**) in a ratio of ca. 1/1.5. Aldehyde **7**, which probably is a precursor of dialdehyde **8**, is detected only in small amounts even at low conversions, indicating that a terminal nonconjugated double bond in **7** is readily hydroformylated under the conditions used. It should be mentioned that in all runs, the product distribution remained nearly the same during the reaction.

Table 1. Hydroformylation of Myrcene (1) Catalyzed by $[Rh(COD)(OAc)]_2$/Phosphine[a]

					selectivity[b] (%)		
run	ligand	P/Rh	time (h)	conversion[b] (%)	**6**	**7**	**8**
1	PPh_3	2	22	35	78	4	13
2	PPh_3	10	13	98	74	4	17
3	PPh_3	20	8	98	76	4	15
4	PPh_3	40	6	98	77	4	15
5	PPh_3	60	11	98	73	4	23
6	PCy_3	10	6	91	75	4	21
7	PCy_3	20	4	90	78	1	20
8	PCy_3	40	6	82	75	4	21

[a] Conditions: myrcene (0.20 M), $[Rh(COD)(OAc)]_2$ (0.25 mM), 80 °C, 80 atm (CO/H_2 = 1/1), solvent toluene. Cy: cyclohexyl. [b] Based on the substrate reacted.

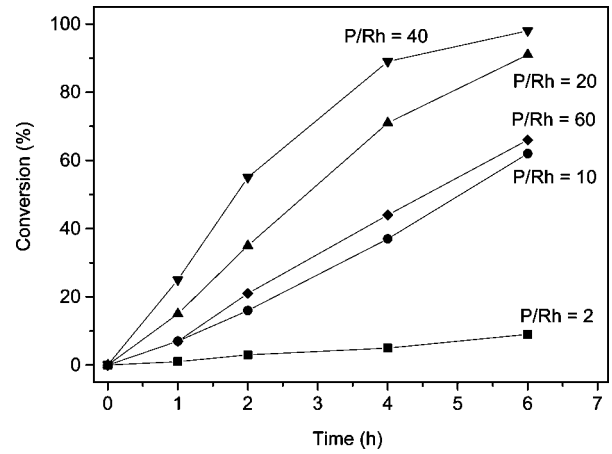

Figure 1. Hydroformylation of myrcene (**1**) catalyzed by $[Rh(COD)(OAc)]_2/PPh_3$ at different P/Rh ratios. Conditions: myrcene (0.20 M), $[Rh(COD)(OAc)]_2$ (0.25 mM), 80 °C, 80 atm (CO/H_2 = 1/1), solvent toluene.

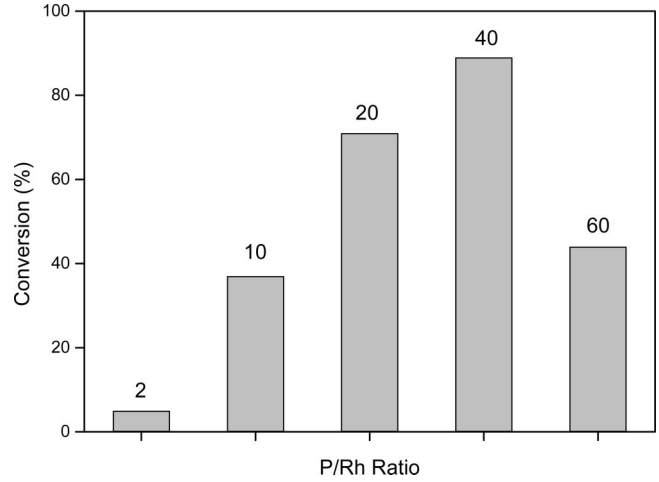

Figure 2. Hydroformylation of myrcene (**1**) catalyzed by $[Rh(COD)(OAc)]_2/PPh_3$ at different P/Rh ratios: conversions for 4 h. Conditions: myrcene (0.20 M), $[Rh(COD)(OAc)]_2$ (0.25 mM), 80 °C, 80 atm (CO/H_2 = 1/1), solvent toluene.

Kinetics curves for the reactions at various P/Rh ratios are presented in Figure 1. The effect of the P/Rh ratio is also illustrated in Figure 2, which shows the conversion of myrcene for 4 h. A strong increase in the reaction rate can be seen when the P/Rh ratio increases from 2 to 40. However, a further addition of the ligand (P/Rh = 60) decelerates the

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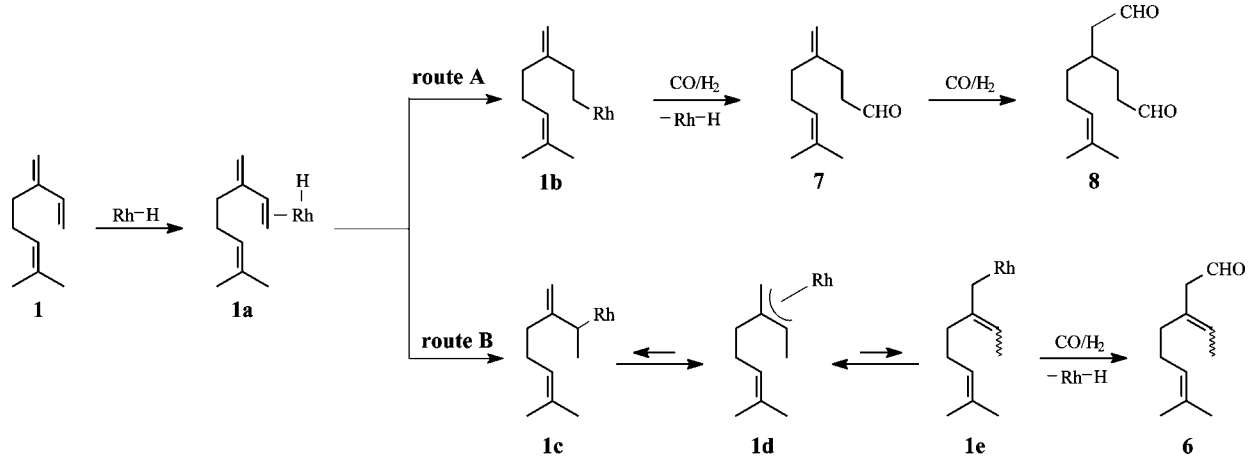
Scheme 2. Proposed Mechanism for the Hydroformylation of Myrcene (1)



reaction (Table 1, run 5). It is important to note that, similar to what has been observed for isoprene,[28] the kinetic curves are nearly straight lines from 0% to 80−90% conversion even at P/Rh = 60, indicating that the substrate competes successfully with the ligand for catalyst sites. In other words, the substrate reacts with rhodium quite readily and most of the metal centers, even at high conversions and high PPh_3 concentrations, contain strongly coordinated myrcene or fragments derived from myrcene.

The structures of aldehydes **6**−**8** show that they result from the reaction of the rhodium catalyst with the less substituted C═C bond of myrcene. A reaction mechanism is presented in Scheme 2. In the migration step, *n*-alkyl (**1b**) and isoalkyl (**1c**) intermediates are formed via anti-Markovnikov and Markovnikov additions, respectively. Intermediate **1b**, reacting with CO and hydrogen, evolves to "linear" aldehyde **7** (route A), whereas **1c** rearranges in η^3-allyl intermediate **1d** and then gives aldehyde **6** (route B). Since the aldehyde derived from the isoalkyl intermediate **1c** was not detected in reaction mixtures, it should be inferred that this $\eta^1-\eta^3$ rearrangement is faster than the CO insertion. Although η^3-allylrhodium complexes are known to be rather resistant to the CO insertion, they can form η^1-allylrhodium species.[23,26] Thus, aldehyde **6** seems to be generated through η^1-allyl intermediate **1e** instead of the direct carbonylation of η^3-allyl intermediate **1d**.

As in the case of isoprene,[28] more than 75% of the products from myrcene are formed by the "allylic" route B, in which the most critical step seems to be the $\eta^3-\eta^1$ rearrangement of **1d** to **1e**. The results obtained in the present study clearly show that this step is strongly accelerated by the increase in the ligand concentration. As conjugated dienes are highly reactive toward rhodium (much more reactive than monoolefins and nonconjugated polyolefins), myrcene successfully competes for rhodium even at high ligand concentrations. Moreover, such conditions favor the formation of η^1-complexes which require only one coordination site, i.e., favor the rearrangement of **1d** to **1e**. On the other hand, high PPh_3 concentrations (P/Rh = 60) decrease the reaction rate, probably, due to the enhanced competition of PPh_3 for the catalyst sites with both myrcene and CO. For myrcene, a limit P/Rh value, i.e., a maximum on the "conversion vs P/Rh ratio" curve (Figure 2), after which the ligand addition is not advantageous any more, is expectedly lower than for isoprene under the same conditions (40 vs 60[28]) because myrcene is a sterically more demanding substrate than isoprene.

The accelerating effect of PPh_3 in hydroformylation at such high P/Rh ratios is quite unusual. In most rhodium systems modified by arylphosphines, an inverse reaction rate dependence on their concentration is commonly observed, at least under "normal" hydroformylation conditions, due to the competition between P-ligands and substrates for coordination sites on rhodium.[31] We suppose that the use of high concentrations of PPh_3, together with relatively mild conditions and high reaction rates, favors the reaction selectivity since in hydroformylation phosphorus ligands are known to suppress undesirable isomerization and hydrogenation side reactions.[31]

Effect of the Ligand Basicity. We have found that the hydroformylation of myrcene can also be accelerated by the increase in ligand basicity. When PPh_3 (θ = 145°, χ = 13.25[32]) was substituted by a much more basic ligand PCy_3 (θ = 170°, χ = 1.40[32]) (Cy: cyclohexyl), the reaction became much faster in spite of a greater steric bulkiness of the latter ligand (Table 1, runs 6 and 7 vs runs 2 and 3). Data on the activity of Rh/PPh_3 and Rh/PCy_3 systems at various P/Rh ratios are presented in Figure 3. It can be seen that up to P/Rh = 20, the more basic ligand PCy_3 (lower χ) shows higher activities. The effect of the ligand basicity on the hydroformylation of myrcene is similar to what has been observed for isoprene[28] and completely opposite to most of the previously reported results for simple olefins.[15,31] Usually, the more basic the phosphines, the less active they are in hydroformylation because they "block" the metal active center due to their strong coordination. The results obtained confirm once again that the hydroformylation of conjugated dienes can be accelerated by favoring the $\eta^3-\eta^1$-rearrangement: the increase in ligand basicity results in stronger competition for the coordination sites on rhodium. At P/Rh = 40, the hydroformylation of myrcene with PCy_3 becomes slower than with PPh_3, probably, because such a great excess of the bulky ligand starts to prejudice the coordination of the substrate (Table 1, run 8 vs run 4).

Effect of Pressure. In general, under "common" hydroformylation conditions (10−50 atm, 70−120 °C), reactions with simple olefins are zeroth order in hydrogen and a negative order in the concentration of CO, the ligand competing with olefin for a place on rhodium.[31] We previously found unusual kinetics

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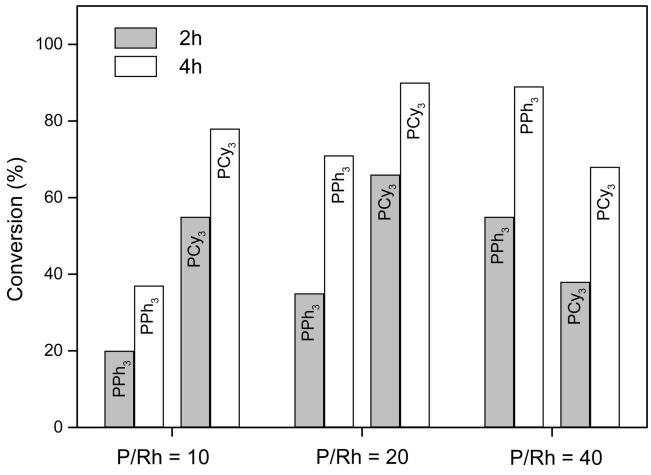


Figure 3. Hydroformylation of myrcene (**1**) catalyzed by [Rh(COD)(OAc)]$_2$/phosphine: ligand effect of at different P/Rh ratios. Conditions: myrcene (0.20 M), [Rh(COD)(OAc)]$_2$ (0.25 mM), 80 °C, 80 atm (CO/H$_2$ = 1/1), solvent toluene.

Table 2. Hydroformylation of Myrcene (1) Catalyzed by [Rh(COD)(OAc)]$_2$/PPh$_3$: Effect of Pressure[a]

run	P(CO) (atm)	P(H$_2$) (atm)	rate[b] (10^{-3} M h^{-1})
1[c]	40	40	54.0
2	10	10	3.4
3	10	40	13.0
4	20	20	12.5
5	40	20	14.0
6	80	20	15.6

[a] Conditions: myrcene (0.20 M), [Rh(COD)(OAc)]$_2$ (0.25 mM), P/Rh = 40, 80 °C, solvent toluene. [b] Initial rate of the conversion of myrcene. [c] A kinetic curve for this run (typical for all others) is presented in Figure1 (P/Rh = 40).

for the hydroformylation of isoprene, which was roughly first order in both hydrogen and CO pressure.[28] The same trends have been observed in the present work with myrcene within a certain range of CO and hydrogen pressures (Table 2, runs 1−4). The reaction is ca. 16 times faster at 80 atm of the equimolar mixture of CO/H$_2$ than at 20 atm (cf. runs 1 and 2). A 4-fold increase in the partial pressure of hydrogen (run 3 vs run 2) or 2-fold increase in both hydrogen and CO (run 4 vs run 2) leads to ca. 4-fold increase in the reaction rate. The positive order in hydrogen suggests that, as in the case of isoprene, the oxidative addition of the hydrogen to rhodium seems to be one of the slowest steps of the catalytic cycle or even the rate-determining one. The effect of CO can be rationalized similarly to that of phosphorus ligands. As for dienes the ability of the catalyst to promote the $\eta^3-\eta^1$-rearrangement is of great importance for its catalytic activity, the concentration of any coordinating ligand is expected to positively affect the reaction rate. No substantial changes in the product distribution have been observed with varying the pressure.

However, when the concentration of CO exceeds that of hydrogen, the increase in the CO pressure does not accelerate proportionally the reaction as the rates are only slightly higher than at CO/H$_2$ = 1 (cf. run 4 with runs 5 and 6, Table 2). Therefore, the excess of CO has to be avoided at the hydroformylation of myrcene because it can prejudice the addition of the hydrogen to rhodium.

The results obtained show that the hydroformylation of myrcene follows roughly the same trends as that of isoprene and also can be readily performed with PPh$_3$ under mild conditions (80 °C, 80 atm) using a large excess of the ligand (P/Rh = 20−40).

Hydroformylation of α-Terpinene, γ-Terpinene, and Terpinolene. We applied the acquired knowledge about such unusual behavior of conjugated dienes to the hydroformylation of monoterpenic dienes with a *p*-menthane structure, i.e., α-terpinene, γ-terpinene, terpinolene, and limonene (the latter substrate is discussed in the next section). All these compounds contain at least one endocyclic double bond, which is usually very resistant to hydroformylation. In α-terpinene (**2**), both double bonds are endocyclic and conjugated; thus, we expected that discovered beneficial effects of the phosphine concentration, ligand basicity, and gas pressure would allow to hydroformylate this substrate under mild conditions using PPh$_3$ as a ligand.

Although the performance of α-terpinene in hydroformylation revealed some similarity with those of isoprene and myrcene, remarkable differences were observed which seem to be related to the cyclic structure of this substrate and a much higher stability of corresponding η^3-allylic complexes under hydroformylation conditions. The cyclic structure of α-terpinene implies that, on the one hand, its double bonds are much more hindered sterically but, on the other hand, they are forced to assume a nearly planar *s-cis* orientation, which is usually less stable than an alternative *s-trans* conformation, a preferred conformation of acyclic conjugated dienes. Conjugated dienes in the *s-cis* conformation are able to form chelate η^4-complexes with transition metals, so that they are expected to be much more susceptible to certain catalytic transformations, e.g., hydrogenation, than those in the *s-trans* conformation.

The data on the hydroformylation of α-terpinene are presented in Tables 3 and 4 as well as in Figure 4. Whereas acyclic conjugated dienes, isoprene and myrcene, have showed almost no reactivity at low PPh$_3$ concentrations; α-terpinene readily reacts at P/Rh < 10 (Table 3, runs 1 and 2). However, only small amounts of aldehydes **9** and **10** (Scheme 3) were observed, the main reaction was the hydrogenation of the substrate.

A possible mechanistic scheme for the transformations of α-terpinene under hydroformylation conditions is presented in Scheme 4. Aldehyde **9** results from the reaction of the rhodium catalyst with the less hindered double bond of α-terpinene, whereas substrate coordination through the other double bond gives aldehyde **10**. Corresponding alkyl intermediates, **2b** and **2e**, can undergo either carbonylation giving the aldehydes or oxidative addition of hydrogen giving the products of the substrate hydrogenation. In addition, **2b** and **2e** can undergo an $\eta^1-\eta^3$ rearrangement resulting in η^3-allyl complexes **2c** and **2f**, respectively. In the case of acyclic conjugated dienes—isoprene and myrcene—the $\eta^1-\eta^3$ rearrangement is faster than a CO insertion and hydrogen addition, as aldehydes derived from corresponding alkyl intermediates (**1c** in Scheme 2 for myrcene) are not observed and the substrate hydrogenation does not occur to a significant extent either. Instead, due to the interaction of the second double bond with rhodium in alkyl rhodium intermediates, stable η^3-allylrhodium complexes are formed, which are resistant to both hydrogenation and CO insertion under the conditions used.

In the case of α-terpinene, its hydrogenation occurs readily at low P/Rh ratios; therefore, it should be inferred that η^1-η^3 rearrangements of intermediates **2b** and **2e** are not so fast (if any) and they have enough time to react with hydrogen, but not with CO. The weaker tendency of rhodium alkyls **2b** and **2e** to form η^3-allyls compared to their acyclic analogues should also be related to their cyclic structure, in which the double bond is highly substituted and is oriented outward from rhodium and the interaction between them is, therefore, sterically disfavored. The rhodium-double bond approximation in **2b** and

Table 3. Hydroformylation of α-Terpinene (2) Catalyzed by [Rh(COD)(OAc)]$_2$/Phosphine[a]

					selectivity[b] (%)			
run	ligand	P/Rh	time (%)	conversion[b] (%)	**9**	**10**	substrate hydrogenation	others
1	PPh_3	2	10	98	4	1	74	21
2	PPh_3	8	10	97	7	2	70	21
3	PPh_3	10	10	60	69	21	7	3
			24	80	68	21	7	4
4	PPh_3	20	10	44	76	23	1	-
			24	70	75	22	1	2
5	PPh_3	40	10	30	76	24		
			24	60	76	24		
6	PPh_3	80	24	9	80	20		
7[c]	PPh_3	10	6	40	52	16	26	6
			10	43	53	16	25	6
			24	55	53	15	24	8
8[c]	PPh_3	20	26	54	60	19	5	16
9	PBz_3	10	10	95	62	15	23	
10	PCy_3	10	10	96	17	2	79	2

[a] Conditions: α-terpinene (0.20 M), [Rh(COD)(OAc)]$_2$ (0.25 mM), 80 °C, 80 atm (CO/H_2 = 1/1), solvent toluene. Bz: CH_2Ph. Cy: cyclohexyl. [b] Based on the substrate reacted. [c] 100 °C.

Table 4. Hydroformylation of α-Terpinene (2) Catalyzed by [Rh(COD)(OAc)]$_2$/PPh_3: Effect of Pressure[a]

					selectivity[b] (%)			
run	*P*(CO) (atm)	*P*(H_2) (atm)	time (h)	conversion[b] (%)	**9**	**10**	substrate hydrogenation	others
1	40	40	6	49	69	20	5	6
2	20	20	6	12	73	17	10	
3	60	40	6	46	72	20	4	4
4	60	20	6	16	76	22		2
5	20	40	6	100			99	1

[a] Conditions: α-terpinene (0.20 M), [Rh(COD)(OAc)]$_2$ (0.25 mM), P/Rh = 10, 80 °C, solvent toluene. [b] Based on the substrate reacted.

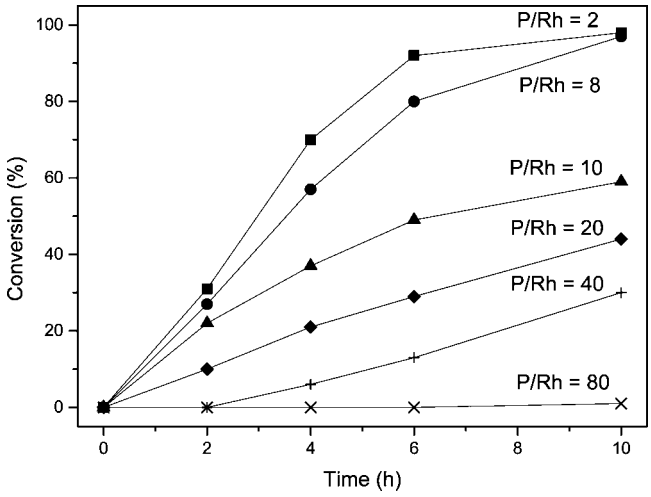
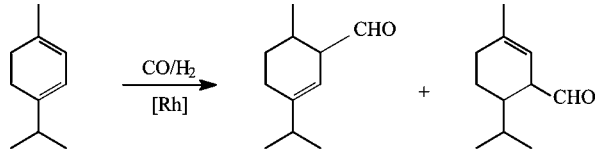


Figure 4. Hydroformylation of α-terpinene (**2**) catalyzed by [Rh(COD)(OAc)]$_2$/PPh_3 at different P/Rh ratios. Conditions: α-terpinene (0.20 M), [Rh(COD)(OAc)]$_2$ (0.25 mM), 80 °C, 80 atm (CO/H_2 = 1/1), solvent toluene.

Scheme 3. Hydroformylation of α-Terpinene (2)



2 **9** **10**

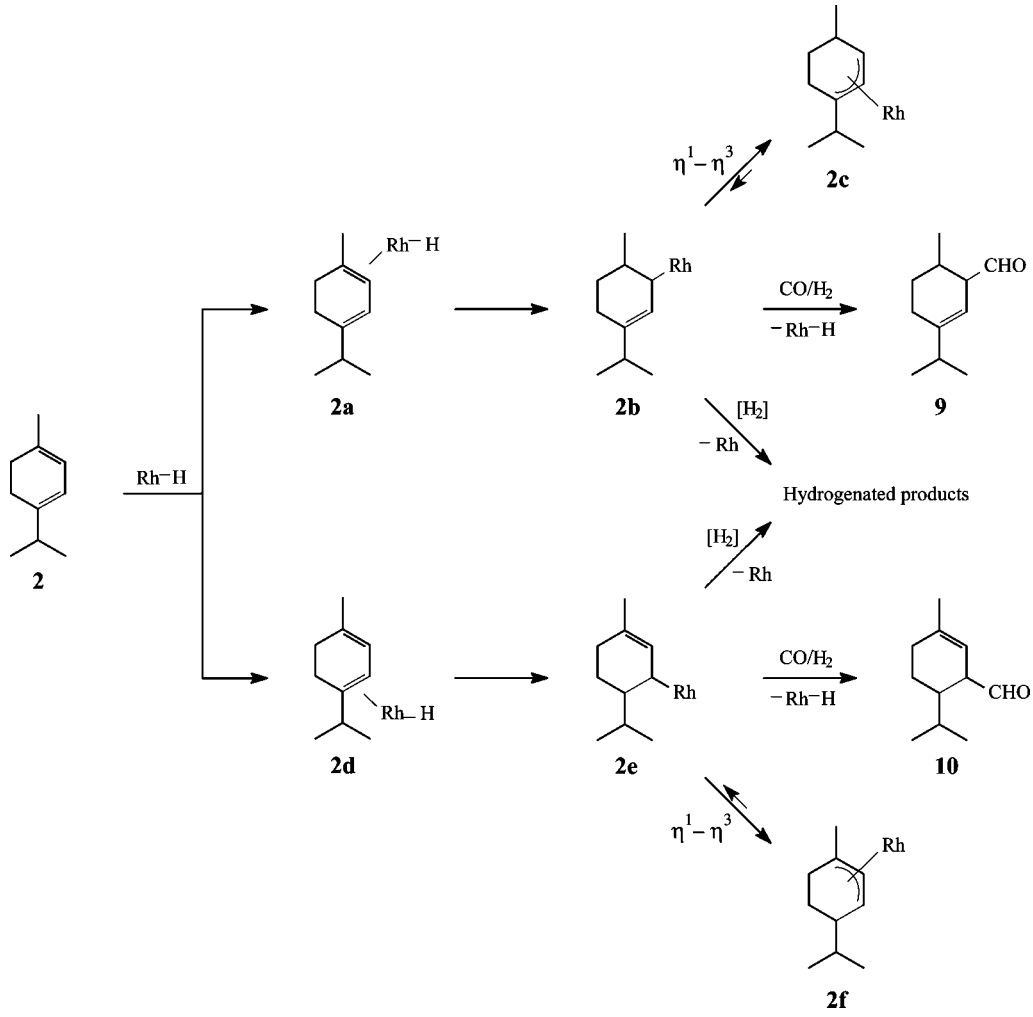
2e is additionally hindered by bulky P-ligands coordinated to rhodium; thus, the formation of η^3-allyls is not as easy as in acyclic intermediate **1c**, where the flexibility of the myrcene fragment allows a more facile coordination of the terminal double bond on rhodium. At P/R*h* ≥ 10, the conversion of α-terpinene occurs slower than at lower P/Rh ratios; however, under these conditions fragrance aldehydes **9** and **10** become the main products (90−100% combined selectivity; Table 3, runs 3−6), with aldehyde **9** accounting for 70−80% of the mass balance. This result is not surprising as it is known that the increase in the PPh_3 concentration usually suppresses hydrogenation and favors carbonylation.[31]

We believe that aldehydes **9** and **10** are generated directly from alkyl intermediates **2b** and **2e** as the increase in the PPh_3 concentration within the "hydroformylation range" (P/Rh = 10−80) slows down the reaction (Figure 5). An opposite trend is expected for the reaction occurring through the intermediate formation of η^3-allyls: a ligand excess would favor the transformation of η^3-allyls into more active η^1-allylrhodium species, similarly to what has been observed with myrcene and isoprene. η^3-Allylrhodium complexes **2c** and **2f**, if formed, are not expected to undergo a direct carbonylation, instead, they have first to rearrange back to **2b** and **2e** and the ligand excess should favor this transformation. In the case of α-terpinene, high concentrations of PPh_3 block the olefin-binding sites on rhodium decreasing the reaction rate, likewise with simple olefins.

All reactions within the "hydroformylation range" become stagnated at near 80% conversion at 80 °C and at near 55% at 100 °C (Table 3). We could not attain a complete conversion of α-terpinene even increasing the reaction time or decreasing the temperature. A possible reason for that could be a deactivation of the catalyst due to the formation of stable η^3-allyl complexes resistant to both carbonylation and hydrogenation in the presence of such a great excess of the P-ligand. Thus, we suspect that η^3-allyl complexes are slowly formed from α-terpinene under hydroformylation conditions; moreover, their formation is near irreversible resulting, therefore, in the catalyst deactivation.

We have also studied the effect of ligand basicity using different monophosphines: PPh_3 ($\theta = 145°$, $\chi = 13.25$), PBz_3 ($\theta = 165°$, $\chi = 10.35$[32]) (Bz, CH_2Ph), and PCy_3 ($\chi = 1.40$, $\theta = 170°$). Although the reaction becomes faster with more basic

Scheme 4. Proposed Mechanism for the Transformations of α-Terpinene (2)



ligands, a contribution of the substrate hydrogenation increases from 7% for PPh_3 to 23% for PBz_3 and to 79% for PCy_3 (Table 3, cf. runs 3, 9, and 10). We suppose that a ligand volume rather than its basicity becomes a decisive factor with α-terpinene. The higher the ligand cone angle, the larger amounts of rhodium active species without P-ligands participate in the reaction; i.e., the higher is the contribution of hydrogenated products because rhodium species without P-ligands promote the hydrogenation of α-terpinene rather then its hydroformylation. In other words, α-terpinene, due to the *s-cis* orientation of its double bonds and their activation by both conjugation and the presence of electron-donating methyl and isopropyl substituents is such a strong and bulky ligand that it captures rhodium species and does not allow the coordination of PBz_3 and PCy_3, which are much more bulky than PPh_3.

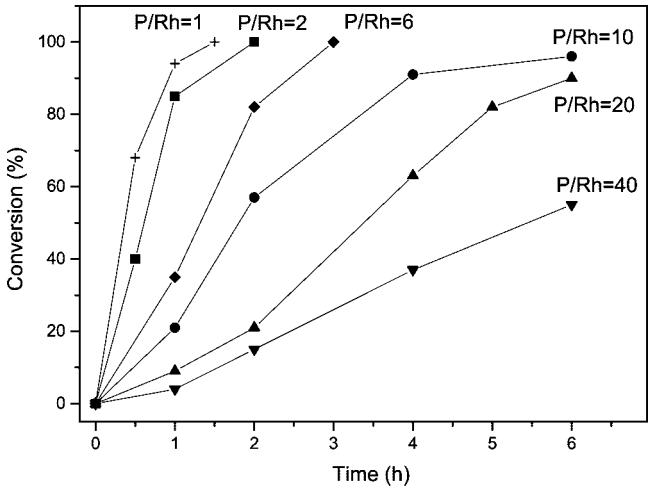


Figure 5. Hydroformylation of limonene (**5**) catalyzed by $[Rh(COD)(OAc)]_2/PPh_3$ at different P/Rh ratios. Conditions: limonene (0.20 M), $[Rh(COD)(OAc)]_2$ (0.25 mM), 80 °C, 80 atm (CO/H_2 = 1/1), solvent toluene.

Thus, differently from acyclic conjugated dienes, two reactions—hydrogenation and hydroformylation—occur concomitantly with α-terpinene under hydroformylation conditions and the balance between them is very complicated. Therefore, it was not surprising for us to observe unusual effects of not only partial pressures of reacting gases but also a CO/H_2 ratio on the reaction rate and product distribution (Table 4). A 2-fold decrease in both hydrogen and CO, at their equimolar proportion, leads to ca. 4-fold decrease in the reaction rate suggesting positive orders in hydrogen, CO, or both (run 2 vs run 1). The increase in only the CO pressure affects neither reaction rate nor selectivity (run 1 vs run 3; run 2 vs run 4). On the other hand, the decrease in the CO pressure completely changes the reaction pathways—the substrate hydrogenation becomes a predominant reaction (run 5 vs run 1). Thus, the hydroformylation of α-terpinene has to be performed at the equimolar CO/H_2 ratio; otherwise, either a rapid hydrogenation of the substrate occurs or no positive effect of CO pressure on the reaction rate is obtained.

Table 5. Reactivity of γ-Terpinene (3) and Terpinolene (4) under Hydroformylation Conditions[a]

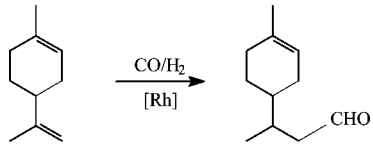
			selectivity[b]		
run	substrate	conversion[b] (%)	substrate hydrogenation	substrate isomerization	hydroformylation[c]
1	**3**	9	26	9	65
2	**4**	10			30

[a] Conditions: substrate (0.20 M), $[Rh(COD)(OAc)]_2$ (0.25 mM), PPh_3 (0.01 M), P/Rh = 20, 80 °C, 80 atm (CO/H_2 = 1/1), 24 h, solvent toluene. [b] Based on the substrate reacted. [c] A mixture of unidentified aldehydes.

Scheme 5. Structures of γ-Terpinene (3) and Terpinolene (4)

3 **4**

Scheme 6. Hydroformylation of Limonene (5)



5 **11**

In Table 5, the data for the hydroformylation of γ-terpinene (**3**) and terpinolene (**4**) (Scheme 5) are presented. Both substrates contain two internal nonconjugated highly substituted double bonds and both have revealed an extremely low reactivity toward hydroformylation. Only 9% of **3** reacted for 24 h under typical conditions applied for the hydroformylation of **1** and **2**; a main reaction was the isomerization of **3** into conjugated diene **2**, which, in its turn, underwent hydrogenation and hydroformylation. A mixture of several aldehydes including **9** and **10** are referred in Table 5 as hydroformylation products. We did not completely characterize minor aldehydes as each of them was formed in small amounts; their chemical nature was estimated based on GC retention times. The isomerization of **3** seems to occur through the formation of η^4-complexes between the substrate and rhodium followed by migration steps (Rh−H addition−elimination−readdition). Terpinolene also showed low reactivity—only 10% reacted after 24 h with no isomerization or hydrogenation products being observed. Traces of several aldehydes were detected by GC, with high-boiling non GC detectable products accounting for ca. 70% of the mass balance.

Thus, the present study reveals a general trend: the endocyclic double bond in *p*-menthane dienes shows reasonable reactivity toward hydroformylation under relatively mild conditions only if it is conjugated with another double bond. The data obtained with limonene (section 3.3) confirm this conclusion.

Hydroformylation of Limonene. The hydroformylation of limonene (**5**) readily occurs under typical conditions used in this work (80 °C, 80 atm) resulting in one aldehyde which is derived from the reaction of the terminal exocyclic bond (aldehyde **11**, Scheme 6). At P/Rh = 1, some isomerization and hydrogenation of limonene are also observed (ca. 15% of the mass balance); while at P/Rh ≥ 2, aldehyde **11** is formed in a 96−99% selectivity. No aldehyde resulting from the hydroformylation of the endocyclic double bond was detected even at longer reaction times and higher temperatures (100−110 °C).

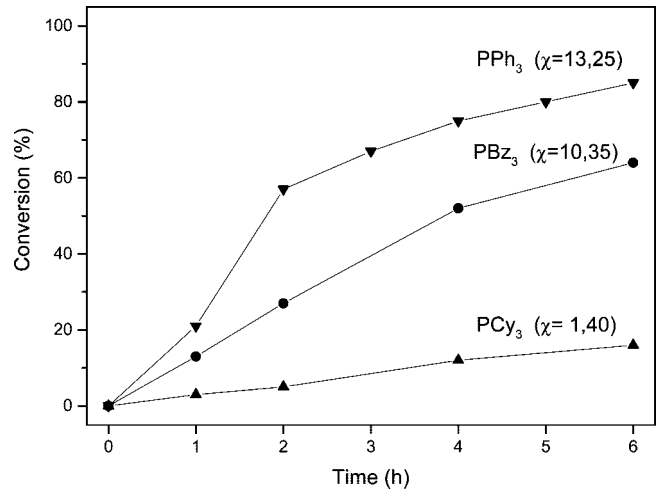


Figure 6. Hydroformylation of limonene (**5**) catalyzed by $[Rh(COD)(OAc)]_2$ with different monophosphines: effect of ligand basicity. Conditions: limonene (0.20 M), $[Rh(COD)(OAc)]_2$ (0.25 mM), P/Rh = 10, 80 °C, 80 atm (CO/H_2 = 1/1), solvent toluene.

Table 6. Hydroformylation of Limonene (5) Catalyzed by $[Rh(COD)(OAc)]_2/PPh_3$: Effect of Pressure[a]

run	*P*(CO) (atm)	*P*(H_2) (atm)	rate[b] (10^{-3} M h^{-1})
1[c]	40	40	44.4
2	40	30	44.0
3	40	20	40.0
4	20	40	90.9
5	20	20	75.0

[a] Conditions: limonene (0.20 M), $[Rh(COD)(OAc)]_2$ (0.25 mM), P/Rh = 10, 80 °C, solvent toluene. [b] Initial rate of the conversion of limonene. [c] A kinetic curve for this run (typical for all others) is presented in Figure6 (P/Rh = 10).

The study of the effects of the reaction variables on the hydroformylation of limonene revealed the trends usually observed with simple olefins. The increase in the concentration of the P-ligand (Figure 5) or ligand basicity (Figure 6) strongly decelerates the reaction due to the competition between the ligand and the substrate for coordination sites on rhodium. The reaction shows usual kinetics, being zeroth order in hydrogen and a negative order in the concentration of CO (Table 6). The decrease in the hydrogen pressure at a constant CO pressure has virtually no effect on the initial rate of the reaction (Table 6, runs 1−3), whereas the decrease in the CO pressure at a constant hydrogen pressure significantly accelerates the reaction (Table 6, run 1 vs run 4; run 3 vs run 5). A negative effect of CO on the reaction rate is a tendency expected for terminal nonconjugated olefins as CO is a ligand competing with limonene for a place on rhodium, likewise phosphine.

Conclusions

The study of the rhodium-catalyzed hydroformylation of monoterpenic polyolefins revealed a remarkable effect of the conjugation of the substrate double bonds on their reactivity. The hydroformylation of myrcene and α-terpinene, the substrates containing conjugated double bonds, can be readily performed under mild conditions using a large excess of PPh_3 and results in two main aldehydes in each case with excellent combined selectivities. The hydroformylation of myrcene follows the trends opposite to those usually observed with simple olefins: the increase in the concentration of the phosphorus ligand, ligand basicity, and pressure of both

hydrogen and CO strongly accelerates the reaction showing that the most critical step is a conversion of η^3-allylrhodium intermediates into much more reactive η^1-complexes. The hydroformylation of α-terpinene does not seem to occur through the formation of η^3-complexes and, at low P/Rh ratios and in systems with more bulky than PPh_3 ligands, such as PBz_3 and PCy_3, is strongly complicated by the hydrogenation of the substrate. The present study reveals that the endocyclic double bond in *p*-menthane dienes can be hydroformylated at a reasonable rate under relatively mild conditions only if it is conjugated with another double bond. γ-Terpinene and terpinolene show an extremely low reactivity toward hydroformylation, whereas in limonene, only a terminal exocyclic double bond reacts with rhodium giving a corresponding aldehyde in almost quantitative yield. Expectedly, the hydroformylation of limonene shows usual kinetics, being zeroth order in hydrogen and a negative order in CO, and common ligand effects: the increase in the ligand concentration or basicity slows down the reaction due to the competition between the ligand and the substrate for the coordination sites on rhodium.

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