JOURNAL OF CATALYSIS 147, 107–114 (1994)

Rhodium-Catalyzed Aldol-Type Chemistry under Syngas: Selective Reductive Dimerizations of Aldehydes to Monoaldehydes and Further Oxidation to *nor*-Ketones

Alfred F. Noels, Rino Messere, Marc Fontaine, and Albert Demonceau

Laboratory of Macromolecular Chemistry and Organic Catalysis, CERM, Institut de Chimie-B6, Université de Liège, B-4000 Sart Tilman, Belgium

Received April 20, 1993; revised October 25, 1993

Under a pressure of syngas in pyridine, $RhCl(PPh_3)_3$ selectively catalyzes the dimerization of enolizable C_n aldehydes, possessing one methylene group in the α-position to the aldehyde function, into saturated dimers, C_{2n} monoaldehydes. The yields are good to moderate. The pressure and relative composition of syngas, together with the use of a triphenylphosphine-ligated metal complex are crucial for obtaining good selectivities. Monosubstitution of the α-carbon severely limits the dimerization. Alcohols and aromatic aldehydes do not react. A tentative reaction mechanism is proposed in which water is involved. The dimer aldehydes can subsequently be oxidized *in situ* by air or various oxidants such as *m*-chloroperbenzoic acid or *t*-butylhydroperoxide into the corresponding *nor*-ketones. This process constitutes a novel access to such ketones.

1. INTRODUCTION

Although the generation and reactions of oxygen-bound early transition metal enolates have been extensively explored and have found use in controlling the stereochemistry in aldol reactions with aldehydes (1), there are only a few reports of aldol-type coupling *catalyzed* by late transition metals (2). Slough *et al.* (3) have recently described an efficient route for the synthesis of oxygen-bound rhodium enolates. Their fully characterized complexes were shown to be able to initiate a catalytic cycle with non-enolizable aldehydes (albeit with a modest turnover number). However, proton transfer between rhodium enolate and enolizable aldehydes seriously limited the applications of the process.

We now report on a new rhodium-based system that efficiently catalyzes, under carefully controlled reaction conditions, the selective coupling of enolizable C_n aldehydes to saturated C_{2n} monoaldehydes, according to Scheme I.

Further, those α-substituted aldehydes can easily be oxidized *in situ* to C_{2n-1} ketones (Scheme II).

To the best of our knowledge, there are only two mentions of systems describing the formation of dimer aldehydes in the literature: one in a patent (4a) and one by Uchida and Matsuda (4b,c) where, in the course of propylene hydroformylation catalyzed by dicobalt octacarbonyl, addition of organic bases (especially pyridine) and of "modifiers" (e.g., magnesium methylate) promoted the formation of modest amounts of dimer aldehydes. Among related reactions, the dimerization of alcohols by tertiary phosphine complexes of Group VIII metals in homogeneous phase involving intermediate formation of aldehydes is especially worthy of note (5). However, alcohols remain unaffected in our reaction conditions.

2. EXPERIMENTAL

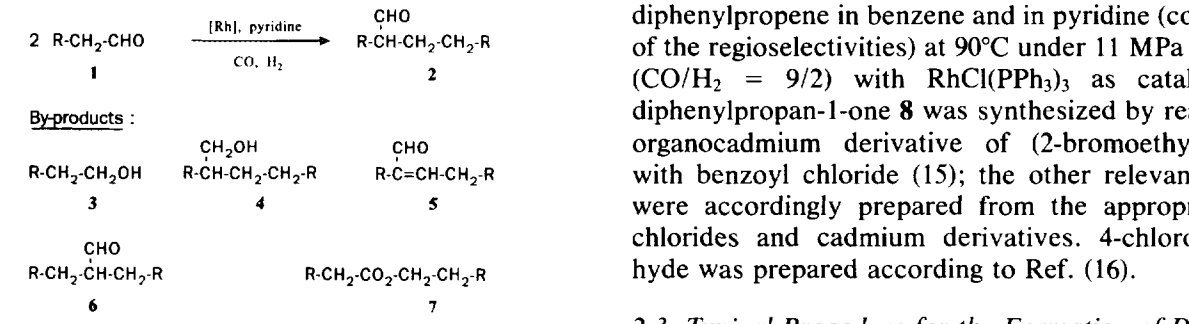
2.1. General Methods

^1H and ^{13}C NMR spectra were obtained on a 400-MHz spectrometer in $CDCl_3$ with TMS as an internal standard. FTIR spectra were recorded in the gas phase (unless otherwise stated) on a spectrometer coupled to a gas chromatograph. GC analysis of organic compounds was carried out on three different fused silica capillary columns (FID with nitrogen as carrier gas): a 30 m × 0.53 mm WCOT, CP-Sil8-CB column (Chrompack), a 30 m × 0.32 mm WCOT, FFAP-CB column (RSL), and (for separations before FTIR) a 30 m × 0.32 mm polydimethylsiloxane-CB column (RSL 150). Both carbon dioxide and carbon monoxide were analyzed on a 2-m column packed with Spherocarb 80/100-GCA-012 (catharometer with He as carrier gas).

2.2. Materials

The reactants (aldehydes) and solvents (pyridines) are commercially available (Janssen Chimica). The aldehydes were distilled before use and kept under nitrogen.

0021-9517/94 $6.00

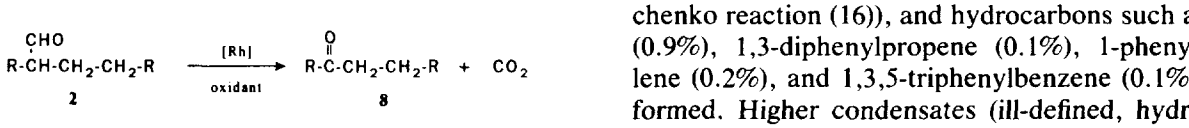


SCHEME I. Reactions of C_n aldehydes **1** to dimer aldehydes C_{2n} **2** and main by-products (**3–7**).

Pyridine was distilled from and kept over KOH pellets under nitrogen.

Catalysts. $RhCl(PPh_3)_3$, $RhClCO(PPh_3)_2$, and $RhH(CO)(PPh_3)_3$ were prepared according to Ref. (6), dimer $Rh_2Cl_2(COD)_2$ according to Ref. (7), and $Rh_2Cp^*_2Cl_4$ according to Ref. (8). $Rh_2Lut_2(COD)_2$ was synthesized from $Rh_2Cl_2(COD)_2$ according to the procedure of Cheli *et al.* (9). Dirhodium tetrafluoroacetate was prepared by exchange from the corresponding acetate (10) and was further purified by chromatography on silica gel 60 (Merck, 35–70 mesh ASTM) with acetone as eluent. $IrCOCl(PPh_3)_2$ was prepared according to Ref. (11).

All the molecules synthesized in this work are described in the literature. All the reaction products of phenylacetaldehyde (except those present in trace amounts) were isolated by standard procedures and compared with authentic samples. Molecules not isolated in the pure state were identified by comparison of their retention times on at least two different GC capillary columns and spectroscopically by coupled GC-FTIR and GC-MS. All the reactions were carried out at least twice. The results were reproducible within 5%. Yields were calculated by GC with dibenzyl as an internal standard, after calibration and introduction of substance-specific correction factors (12) for the most important products. 1,3-Diphenylpropene was synthesized according to Ref. (13); 2,4-diphenylbut-2-enal (**5**, R = Ph) and 5-formylundec-5-ene (**5**, R = *n*-Bu) were synthesized by aldolization of phenylacetaldehyde and hexanal, respectively, according to the standard procedure (14); 1,4-diphenylbutanal **2** was prepared by hydroformylation of 1,3-diphenylpropene in benzene and in pyridine (comparison of the regioselectivities) at 90°C under 11 MPa of syngas (CO/H_2 = 9/2) with $RhCl(PPh_3)_3$ as catalyst. 1,3-diphenylpropan-1-one **8** was synthesized by reacting the organocadmium derivative of (2-bromoethyl)benzene with benzoyl chloride (15); the other relevant ketones were accordingly prepared from the appropriate acid chlorides and cadmium derivatives. 4-chloroacetaldehyde was prepared according to Ref. (16).



SCHEME II. Oxidation reaction of α-substituted aldehydes **2** to *nor*-ketones **8**.

2.3. *Typical Procedure for the Formation of Dimer Aldehydes* 2

A quantity of 11 mmol of the aldehyde, 0.065 mmol of $RhCl(PPh_3)_3$, and 10 ml of dry pyridine were rapidly introduced into a Pyrex lined stainless-steel autoclave under air. The system was then closed and purged once with carbon monoxide. After the total pressure of syngas was set to 11 MPa (with a ratio CO/H_2 = 9/2 for aromatic aldehydes and 8/3 for aliphatic aldehydes), the autoclave was heated to 140°C (160°C with aliphatic aldehydes) for 12 h. After cooling and degassing, the homogeneous brown-yellow solution was kept under nitrogen and aliquots were removed for analysis.

2.4. *Typical Procedure for the Oxidation of* 2

2 ml of the pyridine solution of dimer aldehyde **2** was syringed into a 10-ml flask equipped with a gas bubbler and kept under nitrogen. Weighed amounts of the solid oxidant, e.g., *m*-chloroperbenzoic acid (MCPBA), were then added and the kinetics of the oxidation followed by GC. Oxygen was directly bubbled into the solution.

3. RESULTS AND DISCUSSION

3.1. *Reactions of Phenylacetaldehyde*

Under the optimized conditions detailed in the experimental section (catalyst, pressure of syngas, 140°C in pyridine), phenylacetaldehyde **1** (R = Ph) is selectively converted into 2,4-diphenylbutanal **2** (Scheme 1, R = Ph). Conversion of 96% (i.e., 4% of **1** is recovered unchanged) with a selectivity to **2** of 80% can be attained after 12 h. The main by-products are 2-phenylethanol **3**, 2,4-diphenylbut-2-enal **5** (Table 1), and dibenzylacetaldehyde **6**. However, the amount of the latter by-product **6** is usually below 2%.

In addition, small amounts of 2,4-diphenylbutan-1-ol **4**, phenethylphenetoate **7** (0.6%, resulting from a Tishchenko reaction (16)), and hydrocarbons such as toluene (0.9%), 1,3-diphenylpropene (0.1%), 1-phenylnaphthalene (0.2%), and 1,3,5-triphenylbenzene (0.1%) are also formed. Higher condensates (ill-defined, hydroxyl-containing oligomers which can be precipitated from hexane) account for the balance of the reaction. The correspond-

TABLE 1

Effect of the Solvent on the Yield of Dimer Aldehyde

pK_b	Solvent	Conversion (%)	Yield (%)			
		1	2	3	4	5
8.8	Pyridine	96	80	2	<0.1	1.5
8.1	2-Picoline	85	62	3	0.4	3.5
8.0	4-Picoline	96	68	1	1.8	1
7.4	2,6-Lutidine	96	65	2	3	18
3.2	Triethylamine	95	76	2	4	13
8.9	*N,N*-Dimethylaniline	93	58	2	1	<0.1
—	Benzene	62	4	18	2.8	1
—	Ethanol	81	22	6	1.8	1.5
—	THF	78	23	37	7	0
—	DMSO/pyridine 1/1	19	14	<0.1	<0.1	6

Note. Reaction conditions: 10 ml solvent, 11 mmol phenylacetaldehyde, 6.5×10^{-2} mmol $RhCl(PPh_3)_3$, P_{CO} = 9 MPa, P_{H_2} = 2 MPa, T = 140°C, reaction time = 12 h.

ing ketone, 1-phenyl-2-propanone, does not react under the same conditions.

3.1.1. Influence of the solvent. To obtain a high-yield synthesis of **2** (see Table 1) it is necessary to carry out the reaction in a basic solvent, preferably pyridine. Triethylamine or substituted pyridines, especially 2,6-lutidine (Lut), are less selective but give an even higher yield of coupled products **2** + **5**. THF, DMSO, and *N,N*-dimethylaniline (which has about the same pK_b as pyridine in water) are less efficient as solvents. No or very little aldol condensation takes place in neat pyridine (Table 3, entry 1). This was expected since on the one hand tertiary amines are known to be poor catalysts for promoting aldol condensations and on the other hand excess base favors the retro-process (cleavage of aldols to reactants (18)). The promoting effect of PPh_3 is somewhat more surprising (Table 3, entry 18) and to the best of our knowledge has never been reported.

3.1.2. Influence of the pressure and temperature. Both carbon monoxide and hydrogen are necessary for observing the high yield synthesis of **2** (Table 2). A pressure of at least 9 MPa of CO is needed. A moderate pressure of H_2 helps to increase the yield without significantly promoting the reduction of **1** or **2**. Interestingly, the relative amount of the unsaturated dimer **5** is not much increased in the absence of hydrogen, a first indication that **2** does not necessarily result from the reduction of enal **5** by hydrogen (see below). Note also that under pure nitrogen both alcohol **3** and enal **5** (unsaturated) are simultaneously formed in about equimolecular amounts, indicating the formation of different catalytic species which promote a hydrogen transfer to the reactant rather than to the product in that particular case. The yield of **2** is maximum at 140–145°C. At higher temperatures, the formation of secondary products takes over while the efficiency of the system significantly decreases below 140°C. Under the same reaction conditions, styrene is hydroformylated, mostly to the branched aldehyde, with an overall yield of 95% (branched/linear = 9.6).

3.1.3. Influence of the catalyst. A number of transition metal complexes have been tested under our experimental conditions. Only cobalt-based and rhodium-based systems proved efficient to catalyze selective reactions. Dicobalt octacarbonyl promotes the formation of dibenzylketone from phenylacetaldehyde (19) and the dimerization of styrene (20). Table 3 summarizes the efficiencies and specificities of a variety of rhodium complexes in pyridine.

Although it was conceivable that under a pressure of syngas most of the catalyst precursors could end up as the same species, this is clearly not the case. Actually, the most efficient and selective systems are those containing at least one triphenylphosphine ligand, and Wilkinson's complex proved to be the catalyst of choice. Aldehydes are not reduced to alcohols, in accordance with what is usually observed in rhodium-catalyzed hydroformylations of olefins. More basic phosphines (e.g., tricyclohexylphosphine), phosphites, or an excess of triphenylphosphine lead to inefficient catalyst systems. Moreover, the addition of phosphines to a complex with labile ligands such as $Rh_2Cl_2(COD)_2$ (which is otherwise very poorly active) greatly improves the selectivity of the reaction. This methodology opens a potential route to the synthesis of optically active dimer aldehydes (cf. Table 3, entries 6 to 9).

TABLE 2

Effect of the Pressure on the Yields and Selectivities

Pressure (MPa)			Conversion (%)	Yield (%)			
P_{CO}	P_{H_2}	P_{N_2}	1	2	3	4	5
11	3	0	92	58	4	15	0.8
11	2	0	95	67	3.3	3.8	1.5
9	2	0	97	80	2	<0.1	1.5
8	2	0	96	69	3	0.3	2
6	4	0	99	56	10	3.5	3
10	0	0	96	65	7	0	4
6	0	0	99	45	7	0	1
0.1	0	0	35[a]	0	2	0	15
6	0	4	99	40	9	0	2.5
0	0	10	90	2	43	0	45
0	0	0.1	39	0	16	0	19

Note. Reaction conditions same as in Table 1.

[a] A 4% yield of 1,3-diphenylpropan-2-one is observed.

TABLE 3

Influence of Rh Complexes and of Added Ligands on the Yields and Selectivities

Catalyst	Conversion (%)	Yield (%)			
	1	2	3	4	5
1. No catalyst	8	0	4	0	2
2. $RhCl(PPh_3)_3$	96	80	2	<0.1	1.5
3. $RhF(CO)(PPh_3)_2$	89.4	43	0.8	<0.1	10
4. $RhCl(CO)(PPh_3)_2$	98	72	2	<0.1	2
5. $RhH(CO)(PPh_3)_3$	98	69	6	<0.1	3
6. $RhCl(CO)(PCy_3)_2$	80	46	1.4	0.6	2.5
7. $Rh_2Cl_2(COD)_2$[a]	99.9	<0.1	29	22	<0.1
8. $Rh_2Cl_2(COD)_2$ + 1 PPh_3	69	57	2.2	0.9	2.1
9. $Rh_2Cl_2(COD)_2$ + 3 (−)DIOP[c]	74	64	2	1.6	3
10. $Rh_2Lut_2(COD)_2$	99.5	41	5	28	<0.1
11. $Rh_6(CO)_{16}$[a]	99.9	0.9	29	8	0.4
12. $Rh_2(OOCCH_3)_4$[a]	99.9	0.6	15	14	1
13. $Rh_2(OOCCH_3)_4$ + 1 PPh_3	91.9	57	1.2	0.8	1.2
14. $Rh_2(OOCCF_3)_4$[a]	99.9	0.2	28	6	0.3
15. $Rh_2Cp^*_2Cl_4$	91	48	12	<0.1	4.2
16. $RhCl_3 \cdot n\ H_2O$	91	19	12	<1	5
17. $Ir(CO)Cl(PPh_3)_2$	82	21	0.7	<0.1	40
18. 10 PPh_3[b]	81	3	1.6	<0.1	38
19. $RhCl(PPh_3)_3$ + 10 PPh_3	88	61	4.1	1.9	0.5
20. $RhCl(PPh_3)_3$ + 5 DIPHOS	84	15	2.6	3.6	45
21. $RhCl(PPh_3)_3$ + 10 LiCl	98	78	0.2	1.2	0.2
22. $RhCl(PPh_3)_3$ + 10 LiI	99	69	0.2	1.8	1.5
23. $RhCl(PPh_3)_3$ + 300 Py–O	88	38	1.5	1.6	0.6
24. $RhCl(PPh_3)_3$ + 1000 H_2O	99	92	1	<0.1	0.4
25. $RhCl(PPh_3)_3$ + sieves	97.8	56	<1	<1	1.7

Note. Reaction conditions same as in Table 1.

[a] Formation of mixtures of hydrocarbons (30–60%).

[b] 0.65 mmol, run under nitrogen.

[c] Abbreviations: Cy, Cyclohexyl; COD, 1-5-cyclooctadiene; Cp*, pentamethylcyclopentadienyl; DIOP, 2, 3-*O*-isopropylidene-2, 3-dihydroxy-1, 4-bis(diphenylphosphino) butane; DIPHOS, 1, 2-bis(diphenylphosphino) ethane; Py-O, pyridine-*N*-oxide.

3.1.4. Other phenyl-substituted aldehydes. Benzaldehyde does not self-dimerize; *p*-chlorophenylacetaldehyde yields 40% of 2,4-di(*p*-chlorophenyl)butanal at 99% conversion (not optimized); 2-phenylpropanal yields only 2% of the dimer, showing the dramatic effect of α-substitution on the course of the reaction. Interestingly, 3-phenylpropanal (**1**, R = Bn) and cinnamaldehyde yield the same dimer aldehyde, 2-benzyl-5-phenylpentanal (**2**, R = Bn). That cinnamaldehyde is first reduced to 3-phenylpropanal prior to the coupling reaction was confirmed by sampling the reaction mixture through a high-pressure gas valve. The kinetics of the reaction (Fig. 1) demonstrated not only the fast reduction of the double bond of cinnamaldehyde but also the rather slow formation of dimer aldehydes.

The yield of **2** (R = Bn) is 55% for a 45% conversion (although Fig. 1 indicates a 43% yield, taking samples lowers the overall pressure and consequently the yields; see Table 2). The easy reduction of the double bond of cinnamaldehyde stands in marked contrast with that of the more hindered enal **5** (R = Ph), which under the same reaction conditions is much less susceptible to reduction (see below).

3.2. Reactions of Aliphatic Aldehydes

3.2.1. Reactions of hexanal. Aliphatic aldehydes are expected to be less reactive than phenylacetaldehyde. Indeed, under the same reaction conditions, hexanal (**1**, R = *n*-Bu) yields **2** (R = *n*-Bu) with a rather low yield (34%) but the conversion is then limited to 52%. Conversion can, however, be increased to 70% by raising the reaction temperature to 160°C and the partial pressure of hydrogen to 3 MPa (CO + H_2 = 8 + 3 MPa). Pyridine proved again to be the solvent of choice. The amount of by-products is rather low: about 5% of hexanol, 2% of 5-formylundec-5-ene **5** (R = *n*-Bu), and 1% of *n*-pentane. The results obtained with different catalysts and additives are summarized in Table 4.

More importantly, the formation of **2** (R = *n*-Bu) is substantially improved by addition of a tenfold excess

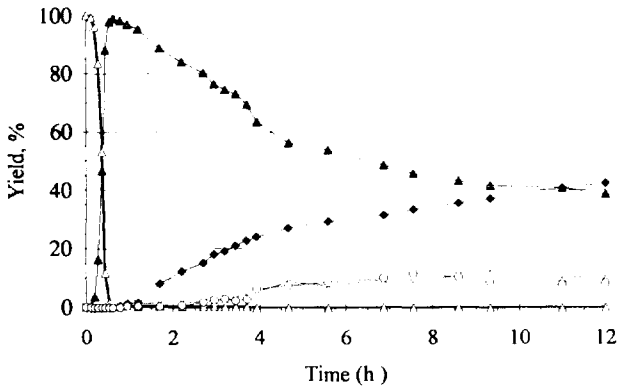


FIG. 1. Reaction of cinnamaldehyde at 140°C. (△) Cinnamaldehyde, (▲) 3-phenylpropanal, (×) 3-phenylpropanol, (♦) dimer aldehyde, and (○) aldol product.

(relative to rhodium) of lithium iodide: *the extrapolated yield at 100% conversion reaches 82%* (Table 4). By contrast, addition of lithium chloride or bromide as cocatalyst shows no beneficial effect and neither of these salts modified the pattern of reaction of phenylacetaldehyde. The presence of an α-methyl group again greatly decreased the tendency towards dimerization, isovaleraldehyde yielding only 8% of dimer (19% conversion). Under the same reaction conditions, crotonaldehyde and tiglaldehyde (2-methyl-2-butenal) do not dimerize.

3.2.2. Cross coupling reactions.

(α) *Phenylacetaldehyde–hexanal.* Under the standardized reaction conditions, use of equimolecular amounts of the aldehydes mostly yields **2**, the products of self-condensation of phenylacetaldehyde (45%), confirming the higher reactivity of the latter, together with 19% of 2-phenyloctanal and a small amount (0.8%) of 2-phenethylhexanal, the cross-coupled products. 5-formylundecane (self-coupling of hexanal) is formed in 8% yield.

(β) *Phenylacetaldehyde–benzaldehyde.* Benzaldehyde itself does not dimerize under our reaction conditions. When mixed with an equimolecular amount of phenylacetaldehyde, 39% of the cross-coupled product, 2,3-diphenylpropanal, is formed, along with 2,4-diphenylbutanal (44%, homocoupling).

TABLE 4

Reaction of Hexanal

Catalyst	Conversion (%) 1	Yield (%) 2	3	5
No catalyst	29	<0.1	1	21
$RhCl(PPh_3)_3$	70	48	5	1.6
$RhCl(CO)(PPh_3)_2$	70	45	5	2
$RhCl(PPh_3)_3$ + 10 LiCl	36	28	6.5	0.8
$RhCl(PPh_3)_3$ + 10 LiBr	66	43	7	1.9
$RhCl(PPh_3)_3$ + 10 LiI	70	58	4	1
$RhCl(PPh_3)_3$ + 300 DMAP	55	32	4	1.9
$Rh_2(OOCH_3)_4$	95	0.5	42	<0.1
$Rh_2Cl_2(COD)_2$	98	0.6	46	0.4
10 LiCl	69	<0.1	5	56
10 PPh_3	22	<0.1	<0.1	15

Note. Reaction conditions: 10 ml pyridine, 11 mmol hexanal, 6.5×10^{-2} mmol $RhCl(PPh_3)_3$; P_{CO} = 8 MPa; P_{H_2} = 3 MPa; T = 160°C; reaction time = 12 h. Abbreviations same as in Table 3.

3.3. Mechanistic Considerations

Although it is not possible to delineate a detailed mechanism precisely, some observations nevertheless stand out:

—The greater part of **2** does not come from the catalyzed hydrogenation of enal **5**. Indeed, it appears that **2** is formed even in the absence of hydrogen (Table 2), although some hydrogen could then be produced by a water–gas shift reaction (the presence of carbon dioxide in the residual gases was demonstrated by GC). Moreover, we confirmed that under our experimental conditions, enal **5** is not significantly reduced to **2** (a few percent at most) as indicated by control experiments with pure **5** (R = Ph) or autoclave tests first run without hydrogen (CO only) then rerun under a pressure of syngas, after the autoclave has been vented. The kinetics of the reaction reported in Fig. 2 also support the hypothesis that **5** is in fact a minor by-product of the reaction.

—Substitution of the carbon atom α to the aldehyde considerably inhibits the dimerization and is indicative of steric interference to the participation of the rhodium catalyst.

—Substituted pyridines as solvent or excess triphenylphosphine also have an adverse effect on the formation of **2**.

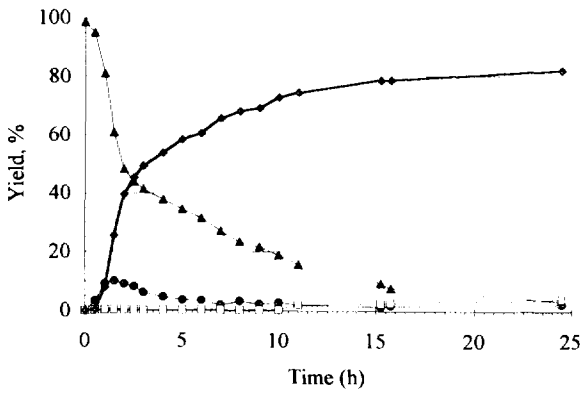


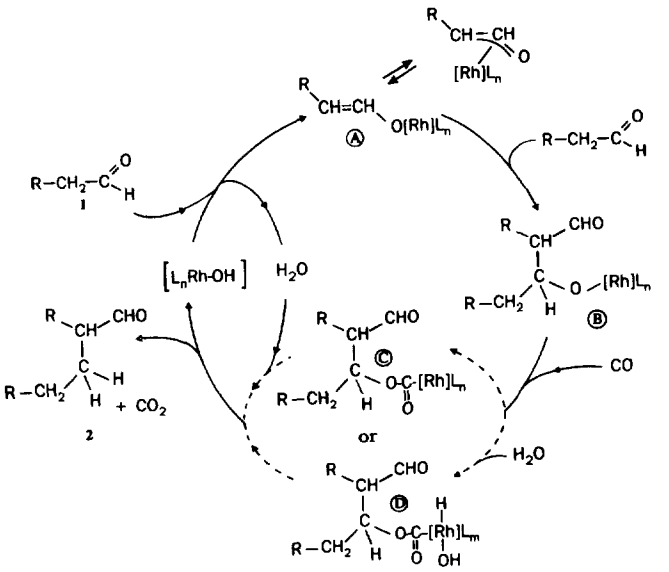
FIG. 2. Reaction of phenylacetaldehyde at 140°C. (●) 2,4-Diphenylbut-2-enal, (▲) phenylacetaldehyde, (□) 2 phenylethanol, and (♦) 2,4-diphenylbutanal.

All these observations are indicative of a coordinative mechanism with a rather crowded transition state. The mechanism can be further delineated by noting that **2** (R = Ph) does not result from the hydroformylation of a possible 1,3-diphenylpropene intermediate. Indeed, in pyridine, diphenylpropene yields **2** and **6** in a ratio of 4 : 1, far from the actual observed ratio of 40 : 1.

Both CO and PPh_3 are needed for efficient catalyst activity. Addition of a small amount of pyridine oxide is detrimental to the catalytic cycle (Table 3, entry 23). Moreover, the remarkable influence of the pressure and of the composition of the gas mixture on the selectivities (see Table 2) points out the existence of several catalytic species and of multiple equilibria between those species in solution. We assume that the role of CO is several fold: to hinder aldehyde decarbonylation; to fine tune (together with the other ligands and solvent) the stereoelectronic requirements of the active species, particularly by adjusting the relative reactivities of the enolate and aldolate (*vide infra*). Although the necessity to carry out the reactions under pressure (autoclaves) and the stability of some intermediates precluded detailed spectroscopic investigations (NMR), samples collected through a high-pressure valve at high catalyst concentration (substrate to rhodium ratio = 5) were amenable to FTIR analysis at atmospheric pressure. As far as the carbonyl region is concerned, the main feature is the appearance of two bands during the course of the reaction, one at 1702 cm^{-1} and one in the overtone bands of pyridine at 1979 cm^{-1}; this latter absorption is characteristic of a carbon monoxide ligated to a metal complex in a square-planar geometry.

The intermediacy of rhodium enolates in aldol chemistry is well documented (3) and permits the rationalization of the first steps of the proposed catalytic cycle that involves enolization of the aldehyde and formation of a rhodium enolate, probably an O-bound or a η^3-oxoallyl species (Scheme III). It has been shown that square planar rhodium halides provide access to oxygen-bound enolates (3). Moreover, such enolates are reported to be more reactive than carbon-bound enolates (2a). Capture of the resulting enolate complex A by free aldehyde yields aldolate B (Scheme III). In this study, formation of oxygen-bound intermediates is supported by the appearance of a weak IR absorption at 1120 cm^{-1} (C–O stretching) in the early stages of the reaction. On the other hand, the band at 1702 cm^{-1} is in agreement with the intermediacy of aldolate B and the low-frequency shift is indicative of ligation of the aldehyde carbonyl to the rhodium centre. It was checked that this absorption comes neither from aldol **3** nor from ketone **8** (*vide infra*).

Extending the mechanistic propositions further becomes more hazardous. The key step is likely to be related to the reaction of the rhodium-oxygen bond in



SCHEME III. Proposed mechanism for the aldehyde coupling reactions.

alkoxide B to eliminate **2** and regenerate an active rhodium species to render the reaction catalytic. Although of current interest, many facets of the chemistry of rhodium alkoxides remain obscure, including hydrogenolysis reactions. It has been shown, however, that late transition-metal alkoxides undergo facile CO insertions to give metal-alkoxycarbonyl complexes (21) (C in Scheme III). Unfortunately, the spectral region where this function is expected to absorb in the IR (around 1630–1640 cm^{-1}) is obscured by a band of pyridinium ion $[C_5H_5NH]^+$ at 1636 cm^{-1}. The chemistry of rhodium alkoxycarbonyls is also rather poorly documented. Since our results indicate that **2** is formed in large amounts, even in the absence of hydrogen, and does not come from a reduction of **5**, hydrogenolysis is unlikely. Among the many other reaction pathways possible, evolution of carbon dioxide after protonolysis (e.g., by PyridineH$^+$, water, or aldehyde) or reaction with a rhodium hydride (which could originate from an oxidative addition of water to Rh(I) species) are the most likely (Scheme III). However, addition of 100 equivalents of pyridinium hydrochloride to the solution modified neither the yields nor the selectivities of the reaction. On the other hand, *addition of water* (100 to 1000 rhodium equivalents) is *beneficial to the reaction*, while addition of 4A molecular sieve, a water scavenger, is detrimental to the synthesis of **2** (Table 3, entries 24 and 25).

Although the rate of formation of **2** is not much modified, a conspicuous reduction of the relative amount of by-products is then apparent and the yield of **2** increases between 1 and 3%, on average. The same effect is also observed with aliphatic aldehydes.

This observation rather supports the intermediacy of rhodium hydrides or hydroxohydrides (complex D in Scheme III). Observation of an elusive, sharp absorption at 2336 cm^{-1}, very rapidly quenched under air, could be indicative of the formation of hydridic species or of a η^2–H_2 molecular complex (22), although the frequency of the absorption seems abnormally high for a rhodium–hydride bond (hydrides were not detected by ^1H NMR) (23). Appearance of a rather broad band at 3415 cm^{-1}, even in experiments carried out under anhydrous conditions, could be related to formation of rhodium hydroxides (water in pyridine absorbs at 3400 cm^{-1} at approximately the same dilution). This attribution is, however, subject to caution, since formation of unusually strong hydrogen bonds is common with late transition metal alkoxides and this absorption could as well be due to water of solvation (24). Relatively few studies of rhodium hydroxide complexes have been undertaken (24) (in comparison to mononuclear hydroxide complexes of platinum(II), which have been comprehensively studied (25)). In any case, the metal should re-enter the cycle as a hydroxorhodium complex, perhaps the real active species. Such species are strong bases that *inter alia* catalyze the hydration of nitriles to carboxamides (25b). They could conceivably be recycled by reacting with aldehyde **1** to give water and enolate A.

3.4. In Situ Oxidation of **2**

As soon as the reaction mixture is contacted with air, a slow, steady transformation of **2** into a new compound takes place. This reaction does not occur as long as the solution is kept under an inert atmosphere, indicating an oxidation reaction. Evolution of a gas, identified as carbon dioxide by GC and reaction with barium hydroxide solution, takes place. The new products were identified (FT-IR, ^{13}C, and ^1H NMR, and comparison with authentic samples) as being the related *nor*-ketone, e.g., 1,3-diphenylpropan-1-one **8**, when R = Ph. The oxidation reaction can be accelerated by addition of oxidants, the relative effectiveness of which for the oxidation of **2** (R = Ph) is

$$\text{MCPBA} > \text{TBHP} > O_2 > Na_2S_2O_8 > \text{air} > BaO_2,$$

where MCPBA stands for *m*-chloroperbenzoic acid and TBHP for *t*-Bu hydroperoxide. MCPBA oxidizes 100% of **2** into **8** with a selectivity of 91% in 12 h at 20°C. The reaction is zero order in oxidant and seems to be first order in the aldehyde **2**. Addition of fresh $RhCl(PPh_3)_3$ to the solution does not modify the rate of oxidation, suggesting the formation of new and very specific rhodium species under pressure. α-Disubstituted aliphatic aldehydes are also oxidized into ketones under the same conditions, albeit more slowly and with lower yields. For example, under the same conditions, 5-formylundecane is oxidized into 5-undecanone with a 38% yield at 69% conversion. Those results, however, are not optimized. This reaction constitutes a novel, selective access to C_{2n-1} ketones from C_n aldehydes. On the other hand, non-α-substituted aldehydes are also oxidized and consequently converted into the *nor*-aldehyde; typically, residual phenylacetaldehyde is slowly converted to benzaldehyde in the reaction medium in the presence of air.

So far, only enzymes such as horseradish peroxidase have been able to promote such transformations, via the formation of dioxetanes or dioxetanones (26, 27). However, definitive assessment of the nature of the intermediates and of the scope of the reaction must await further study.

ACKNOWLEDGMENTS

We thank Prof. P. Teyssié and Prof. A. J. Hubert for their interest in this work and the National Fund for Scientific Research (FNRS), Belgium, for the purchase of major instrumentation.

REFERENCES

1. (a) Evans, D. A., and McGee, L. A., *Tetrahedron Lett.* **21,** 3975 (1980); (b) Yamamoto, Y., and Maruyama, K., *Tetrahedron Lett.* **21,** 4607 (1980); (c) Stille, J. R., and Grubbs, R. H., *J. Am. Chem. Soc.* **105,** 1664 (1983); (d) Sasai, H., Kirio, Y., and Shibasaki, M., *J. Org. Chem.* **55,** 5306 (1990).
2. (a) Sato, S., Matsuda, I., and Izumi, Y., *J. Organomet. Chem.* **352,** 223 (1988) and references cited therein; (b) Doney, J. J., Bergman, R. G., and Heathcock, C. H., *J. Am. Chem. Soc.* **107,** 3724 (1985); (c) Aoyama, Y., Tanaka, Y., Toi, H., and Ogoshi, H., *J. Organomet. Chem.* **329,** 251 (1987); (d) Ito, Y., Aoyama, T., Hirao, T., Mochizuki, A., and Saegusa, T., *J. Am. Chem. Soc.* **101,** 494 (1979); (e) Nakatsuka, M., Kise, M., and Saegusa, T., *Tetrahedron Lett.* **21,** 2873 (1980); (f) Reetz, M., and Vougoukias, A., *Tetrahedron Lett.* **28,** 793 (1987).
3. Slough, G. A., Bergman, R. G., and Heathcock, C. H., *J. Am. Chem. Soc.* **111,** 938 (1989) and references cited therein.
4. (a) U.S. Patent 3,946,082 (1976); (b) Uchida, H., and Matsuda, A., *Bull. Chem. Soc. Jpn.* **36,** 1351 (1963) and *Bull. Chem. Soc. Jpn.* **37,** 373 (1964); (c) "Organic Synthesis via Metal Carbonyls" (I. Wender and P. Pino, Eds), Vol. 2. Wiley–Interscience, New York, 1977.
5. (a) Gregorio, G., Pregaglia, G., and Ugo, R., *Inorg. Chem. Acta* **3,** 89 (1969); (b) Gregorio, G., Pregaglia, G., and Ugo, E., *J. Organomet. Chem.* **37,** 385 (1972).
6. (a) McCleverty, J. A., and Wilkinson, G., *Inorg. Synth.* **8,** 214 (1966); (b) Osborn, J. A., and Wilkinson, G., *Inorg. Synth.* **10,** 67 (1968); (c) Osborn, J. A., and Wilkinson, G., *Inorg. Synth.* **25,** 77 (1990).
7. Giordano, G., and Crabtree, R. H., *Inorg. Synth.* **19,** 218 (1979).
8. Kang, J. W., Moseley, K., Maitlis, P. M., *J. Am. Chem. Soc.* **91,** 5970 (1969).
9. Cheli, D. E., Fanwick, P. E., and Rothwell, I. P., *Organometallics* **9,** 2948 (1990).
10. Johnson, S. A., Hunt, M. R., and Neuman, H. M., *Inorg. Chem.* **2,** 960 (1963).

11. Collman, J. P., Sears, C. T., and Kubota, M., *Inorg. Synth.* **11,** 101 (1968).
12. R. Kaiser, "Tables for gas chromatography" (translated by P. H. Scott), Vol. III, Butterworths, London, 1963.
13. Raunio, E., and Bonner, W. A., *J. Org. Chem.* **31,** 396 (1966).
14. Nielsen, A. T., and Houlihan, W. J., *Org. React. (NY)* **16,** 78 (1968).
15. Vogel, A. I., "Practical Organic Chemistry," 5th ed., pp. 617, 1018. Wiley, New York, 1989.
16. Campà, C., Sanchez-Fernando, F., and Tristan-Polo, M., *Nouv. J. Chim.* **9,** 493 (1985).
17. Ito, T., Horino, H., Koshiro, Y., and Yamamoto, A., *Bull. Chem. Soc. Jpn.* **55,** 504 (1982).
18. Nielson, T. A., and Houlihan, W. J., *Org. React. (NY)* **16,** 1 (1968).
19. Fontaine, M., Noels, A. F., Demonceau, A., and Hubert, A. J., *Tetrahedron Lett.* **31,** 3117 (1990).
20. Fontaine, M., Hubert, A. J., Noels, A. F., Demonceau, A., and Teyssié, P., *J. Organomet. Chem.* **417,** C28 (1991).
21. (a) Bryndza, H. E., and Tam, W., *Chem. Rev.* **88,** 1163 (1988); (b) Kim, Y. J., Osakada, K., Takenaka, A., and Yamamoto, A., *J. Am. Chem. Soc.* **112,** 1096 (1990).
22. Crabtree, R. H., and Hamilton, D. G. *Adv. Organomet. Chem.* **28,** 299 (1988).
23. We thank a referee for suggesting additional possibilities for this absorption which could be linked either to the presence of CO_2 in the solution or to the vibration [ν (P-H)] of a phosphonium salt.
24. (a) Green, L. M., and Meek, D. W., *Organometallics* **8,** 659 (1989); (b) Kegley, S. E., Schaverien, C. J., Freundberger, J. H., and Bergman, R. G., *J. Am. Chem. Soc.* **109,** 6563 (1987).
25. (a) Arnold, D. P., and Bennett, M. A., *J. Organomet. Chem.* **199,** 119 (1980); (b) Jensen, C. M., and Trogler, W. C., *J. Am. Chem. Soc.* **108,** 723 (1986).
26. (a) Nascimento, A. L., and Cilento, G., *Biochim. Biophys. Acta* **843,** 254 (1985); (b) Duran, N., Zinner, K., Vigidal, C. V., and Cilento, G., *Biochem. Biophys. Res. Commun.* **74,** 1146 (1977); (c) Adam, W., Baader, W. J., and Cilento, G., *Biochim. Biophys. Acta* **881,** 330 (1986); (d) Cilento, G., *in* "The Role of Oxygen in Chemistry and Biochemistry" (W. Ando and Y. Moro-oka, Eds.), *Studies in Organic Chemistry,* Vol. 33, p. 435. Elsevier, Amsterdam, 1987.
27. Under the influence of Cu(II) in methanol containing pyridine and Et_3N, phenylacetaldehyde undergoes competitive O_2-dependent conversion to benzaldehyde and phenylglyoxal; see Jin, S.-J., Arora, P. K., and Sayre, L. M., *J. Org. Chem.* **55,** 3011 (1990).