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Hydroxyalkylphosphines in Asymmetric Hydrogenations

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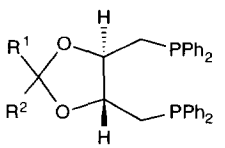
Abstract: The synthesis of chiral bisphosphines bearing a hydroxyl group in a rigid backbone is described. These compounds which are analogues of the prominent ligand DIOP formed definite rhodium complexes. IR spectra provided evidence that the hydroxyl groups do not participate in the complexation to the metal or to one of the acetal oxygen atoms. The complexes have proven successful in the asymmetric hydrogenation of prochiral functionalized olefins in different solvents. In methanol only small effects could be detected in comparison to parent complexes which do not carry a hydroxyl group. However, when hydrogenations were performed in methylene chloride or toluene significant differences in the enantioselectivities (by up to 17 %*ee*) were observed, especially in the reaction with itaconic acid or its dimethyl ester, respectively. In the latter cases the effect is contingent on the spatial orientation of the hydroxyl group in the catalyst.

Introduction

The enantiodifferentiating hydrogenation catalyzed by transition metals bearing chiral chelating bisphosphines has attracted much attention over the last two decades.[1] Notwithstanding the high enantioselectivities reported in numerous reductions, particularly when functionalized olefins are hydrogenated, there are many applications where catalysts based on these phosphines perform poorly in terms of activity and enantioselectivity.[2] In certain instances the introduction of a hydroxyl group into the ligand backbone has been shown to be advantageous for the improvement of the selectivity.[3] These experiments, aimed at the development of ligands equipped with a second ligating functionality in order to support the intrinsic stereodiscriminating ability of the catalyst, have encouraged the synthesis[4] and trial[5] of other chiral hydroxyalkylphosphines.[6] Our recent studies of the complexation behaviour of this new class of ligands and their catalytic properties gave rise to the assumption, that a close neighbourhood between the hydroxyl group and the metal should be avoided in order to provide for an efficient reaction.[7,8] Besides these investigations, it seems that hydroxyalkylphosphines have a great potential for the construction and study of bimetallic compounds.[9] Moreover, they are particularly attractive as precursors for the synthesis of phosphino phosphites which have been shown as powerful ligands in metal-catalyzed asymmetric hydroformylation.[10]

In a preliminary communication we reported the preparation and use of the hydroxyalkylbisphosphine **1a**, which is related to the ligand DIOP (**2b**)[11] in rhodium-catalyzed asymmetric hydrogenations of dehydrophenylalanine derivatives.[12]



1a: $R^1 = C_6H_5$, $R^2 = CH_2OH$
1b: $R^1 = C_6H_5$, $R^2 = CH_3$
2a: $R^1 = CH_3$, $R^2 = CH_2OH$
2b: $R^1 = R^2 = CH_3$
3a: $R^1 = H$, $R^2 = 2\text{-}HO\text{-}C_6H_4$
3b: $R^1 = H$, $R^2 = 4\text{-}HO\text{-}C_6H_4$
3c: $R^1 = H$, $R^2 = C_6H_5$

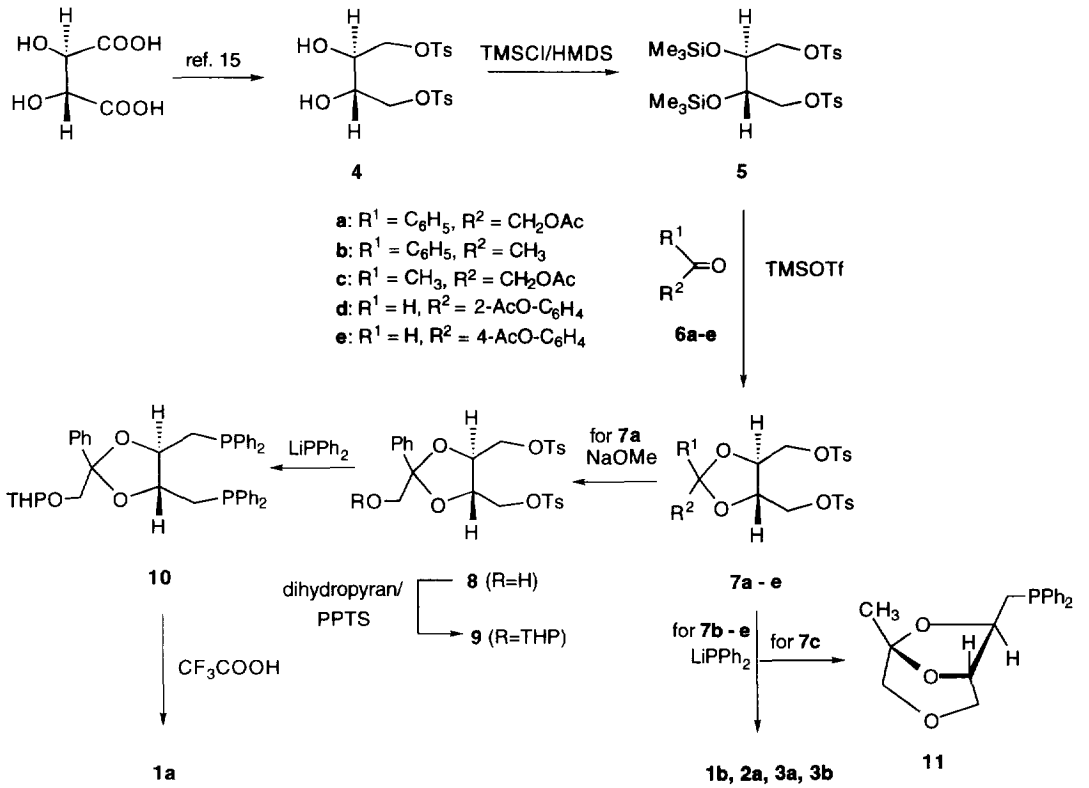
In the hydrogenation of methyl (*Z*)-2-N-acetamidocinnamate (AMe) improved enantioselectivity was observed in comparison with the derivative **1b**[13], which presents another derivative of DIOP. However, a small loss of enantioselectivity has been observed in the hydrogenation of (*Z*)-2-N-acetamidocinnamic acid (AH). Based on the relevance of these results our interest has been focused on a more detailed study of the complex derived from the new ligand. Additionally, here we wish to present our results on the synthesis of related hydroxyalkylphosphines **2a, 3a** and **3b** and to compare them in the asymmetric hydrogenation in comparison with the parent catalysts containing DIOP (**2b**) or **3c**[14], respectively.

Results and Discussion

Preparation of the new ligands and complexes. For both synthetic pathways presented here the bissilyl derivative **5** has been revealed as a key precursor (Scheme 1). It could be synthesized by silylation of the free hydroxyl groups of the diol **4**[15] with a mixture of hexamethyldisilazane (HMDS) and trimethylsilyl chloride (TMSCl). Acetalization of this compound with **6a-e** using trimethylsilyl trifluoromethanesuifonate (TMSOTf) as catalyst[16] furnished the dioxolane derivatives **7a-e** in good yields.

Our original procedure for the preparation of the hydroxyalkylphosphine **1a** involved the exchange of the base sensitive O-acetyl group by an acetal protective group in order to circumvent problems which could arise during the substitution of the tosyl groups by phosphide.[12] Thus, deacetylation of the substituted acetophenone derivative **7a** took place with catalytic sodium methanolate and furnished **8**. The alcohol **8** was in turn converted into the tetrahydropyranyl ether **9**.[17] Replacement of both tosyl groups was readily accomplished by reaction with lithium diphenylphosphide to give the 1,4-bisdiphenylphosphine **10** in a good yield. Finally, cleavage of the protecting group with catalytic amounts of trifluoracetic acid in methanol[4b] gave the desired hydroxyl ligand **1a**. For the synthesis of the derivative **1b** the corresponding acetal **7b** could be directly converted into the phosphine.

In this paper we report that the implementation of the latter methodology for the synthesis of hydroxyalkylphosphines such as **2a, 3a** and **3b** starting from the corresponding acetals was similarly successful. It is worth mentioning that during the reaction with phosphide simultaneously the O-acetyl group was lost. The bisphosphines could be obtained in moderate to good yields.



Scheme 1

The diminished yield of **2a** was due to the formation of the cyclic alkylation product **11**. However, the newly disclosed pathway avoids the tedious exchange of the O-protective groups and does not lower the overall yield. The monophosphine **11** was isolated and fully characterized. It might possibly serve as a bulky monodentate ligand in asymmetric reactions.

Treatment of the new phosphine ligands with [Rh(COD)acac] and subsequent addition of aqueous HBF_4 produced the catalyst precursors [Rh(COD)(bisphosphine)]BF_4.[18] This method of preparation gave higher yields of complexes than the often used procedure of mixing [$Rh(COD)_2$]BF_4 with the bisphosphine.

NMR and IR spectra were recorded for all compounds newly synthesized. The assignment of the ^{31}P-NMR resonances of the hydroxyalkylphosphines and their complexes is given in Table 1. It is interesting to note that for the bisphosphine **1a** only one signal could be observed in $CDCl_3$ although the compound does not possess C_2-symmetry like DIOP. However, after complex formation both phosphine groups appeared as well separated double doublets with ^{103}Rh-^{31}P coupling constants of 144.0 Hz and 143.8 Hz, respectively, and a uniform ^{31}P-^{31}P coupling of 36.6 Hz. Similar NMR data were observed for **2a, 3a** and **3b** and their corresponding complexes. The IR spectra of the ligands were characterized by OH bands of similar wavelength. In all cases as Rh complexes were formed shifts to higher wavenumbers were observed. It is noteworthy that both phenol complexes derived from **3a** and **3b** show OH valence bands at comparable wavelengths. From all these data it can be concluded that association of the hydroxyl group to the metal does

not take place.[19] Moreover, there is no conceivable intramolecular hydrogen bond (with the exception of **3b**) between the hydroxyl group and one acetal oxygen, which should appreciably influence the conformation of the chelate.

Table 1. Selected IR and ^{31}P-NMR data for hydroxyalkylbisphosphines and their Rh complexes

Ligand or complex	^{31}P NMR [a]	IR (ν_{OH})	
	δ [ppm]	cm^{-1}	Δcm^{-1}
1a	-22.7	3433 *s* [b]	
[Rh(COD)(**1a**)]BF_4	13.7/13.2	3540 *s* [b]	107
2a	-23.1/-23.4	3431 *m* [d]	
[Rh(COD)(**2a**)]BF_4	13.5/12.3	3442 *s* [b]	11
3a	-22.8/-23.6	3411 *m* [d]	
[Rh(COD)(**3a**)]BF_4	14.0/13.0	3423 *m* [c]	12
3b	-22.6/-22.1	3399 *m* [b]	
[Rh(COD)(**3b**)]BF_4	13.5/13.8	3424 *m* [c]	25

[a] All Rh complexes gave double doublets due to the ^{103}Rh-^{31}P and ^{31}P-^{31}P couplings. [b] Measured in KBr. [c] Measured in polychlortrifluorethylene. [d] Neat.

Asymmetric hydrogenation. To evaluate the properties of the new hydroxyl catalysts **1a**, **2a** and **3a,b** in different solvents they were tested in the asymmetric hydrogenation of selected prochiral olefins in methanol, methylene chloride or toluene, respectively. Relevant results are listed in Table 2. For the purpose of comparison, results, which were achieved with the cationic complexes of the hydroxyl group free ligands **1b,** DIOP (**2b**) or **3c**, respectively, were likewise added into the table.

Several features warrant comment. In methanol, all catalysts hydrogenated the substrates very fast.[20,21] This observation indicates that the hydroxyl group in the complexes derived from **1a**, **2a** or **3a,b** as expected does not strongly interact with the metal or the substrate during the catalysis. Apparently, this property can be traced to the rigid construction of the ligands as well as to the remote position of the hydroxyl group.[22] The highest enantiomeric excess in the hydrogenation of AH was obtained when ligand **3b** was employed. The catalysts derived from the ligands **2a**, **2b** (DIOP), **3a** and **3c** hydrogenated the same substrate with slightly lower %*ee*. Comparable intrinsic stereodiscriminating abilities of these five complexes were also observed in the hydrogenation of itaconic acid, which will be discussed below. In comparison with these catalysts, severely diminished selectivities were obtained with the complexes of type **1** in the hydrogenation of AH. When AMe was hydrogenated in the presence of ligands of type **2** or **3** a uniform decrease of the %*ee* was found in comparison with the results obtained with AH. In contrast, both catalysts based on the structure **1** were more efficient in the reaction with AMe than in the hydrogenation of AH. In general, those catalysts which bear a hydroxyl group gave slightly higher %*ee* in the hydrogenation of AMe than the parent catalysts, whereas in case of AH as substrate this weakly pronounced tendency (with the exception of **3b**) was reversed.[23]

Table 2. Hydrogenation of prochiral olefins with [Rh(COD)L*]BF_4 [a]

Ligand (L*)	Solvent	AH		AMe		ItH_2		$ItMe_2$	
		time [b] [min]	%ee [c]	time [b] [min]	%ee [c]	time [b] [min]	%ee [c]	time [b] [min]	%ee [c]
1a	MeOH	< 2	59.3	< 2	73.6	< 2 [d]	30.8	5 [d]	31.7
1b	MeOH	< 2 [d]	61.2	< 2	68.7	< 2 [d]	32.8	7 [d]	28.5
1a	CH_2Cl_2	10	60.7	5.5	73.9	27	61.0	3.5	21.4
1b	CH_2Cl_2	15	69.7	5	68.8	30	49.3	3	21.5
1a	toluene	280	35.5	24	51.6	1800	51.4 [e]	1140	18.5
1b	toluene	150	31.1	25	46.5	1020	34.7 [e]	285	33.8
2a	MeOH	< 2 [d]	78.4	< 2 [d]	69.2	< 2 [d]	65.3	8 [d]	25.5
2b	MeOH	< 2 [d]	78.9	< 2 [d]	67.6	< 2 [d]	64.0 [f]	8 [d]	30.4 [g]
2a	CH_2Cl_2	12	61.4	10	74.5	30	67.6	4	20.5
2b	CH_2Cl_2	13	67.9	5.5	68.3	30	57.4	3	28.4
2a	toluene	138	42.2	18	47.7	1200	56.4 [e]	600	11.5
2b	toluene	150	35.7	10	48.0	1020	39.3 [e]	510	27.4
3a	MeOH	< 2 [d]	78.1	< 2 [d]	71.7	< 2 [d]	63.9	8 [d]	33.4
3b	MeOH	< 2 [d]	79.5	< 2 [d]	69.8	< 2	68.9	4.5	29.8
3c	MeOH	< 2	78.3	< 2	68.4	< 2	65.9	4	28.2
3a	CH_2Cl_2	11	71.2	3.5	71.6	23	53.4	3.5	12.6
3b	CH_2Cl_2	12	74.2	3	71.3	25	47.7	2.2	18.5
3c	CH_2Cl_2	12	62.8	5	68.5	25	47.7	2.5	17.7

[a] If not otherwise stated: molar ratio substrate:catalyst = 100:1; 1 mmol substrate in 15 mL solvent; 1 atm total pressure above the reaction mixture, 25 °C. [b] measured after 100 % conversion. [c] measured on the crude product, g.c. with a chiral column: for (*R*)-N-acetyl phenylalanine and (*S*)-methyl succinic acid after esterification with diazomethane or trimethylsilyl diazomethane, respectively, and for methyl ester of (*R*)-N-acetyl phenylalanine and (*S*)-methyl succinate, respectively, with XE 60-L-valine tert-butylamide, 150 °C; if not otherwise stated reproducible within ±1 %*ee*. [d] molar ratio substrate:catalyst = 200:1. [e] reproducible within ±3 %*ee*. [f] ref. 24: 88 % conversion, 62 %*ee* (*S*) in the presence of 1 equivalent NEt_3. [g] ref. 24: at 30 °C, 44 % conversion, 10 %*ee* (*S*).

The hydrogenation of itaconic acid (ItH_2) and its dimethyl ester ($ItMe_2$) was also examined.[25] As peculiar substrates they afford the possibility of competitive binding of the α- or ß-carboxylate moiety to the rhodium. Moreover, due to the presence of these two carboxylate groups they represent potential candidates able to perform a desired secondary interaction with the hydroxyl group of the phosphine ligand. In general, in the hydrogenation of ItH_2 the catalysts based on the structures **2** and **3** were superior to the complexes of type **1**. In the most cases more or less distinct alterations in selectivity were caused by the remote functional group. Thus, with hydroxyl catalysts **1a** and **3a** diminished selectivities compared to those of the parent

catalysts were obtained in the reaction with ItH_2, whereas the same catalysts performed better than the parent catalysts in the hydrogenation of $ItMe_2$. It is interesting to note that for the catalysts of type **2** this tendency is reversed for the concerned pairs of complexes and substrates.[26]

To give the hydroxyl group in the catalysts based on the hydroxyl ligands a better chance to interact with the substrate, hydrogenations in CH_2Cl_2 and toluene were also performed. The change from methanol to these less polar solvents significantly influenced the course of the catalysis. Thus, diminished rates were observed for all catalysts in comparison with the reaction in methanol (the only exception is the hydrogenation of $ItMe_2$ in CH_2Cl_2). Especially when the reduction was performed in toluene low reactivities of the catalysts resulted. This behaviour, which was independent from the presence of a hydroxyl group in the metal complex, might be attributed to the poor solubility of the substrate or the precatalyst,[27] respectively. Likely due to these properties results obtained with catalysts based on **3** in toluene could only be poorly reproduced.[28] Therefore these data are omitted from the table. However in general, the measurements in CH_2Cl_2 and toluene always confirmed the same tendency.

Thus, when AMe was hydrogenated in CH_2Cl_2 or toluene, in most cases elevated enantioselectivies were obtained with the hydroxyl ligands, although for all catalysts a general decrease of the %*ee* was found in toluene. The increase in selectivity caused by the hydroxyl group is in keeping with the same, but more weakly marked tendency observed in methanol. For AH a similar trend was observed in toluene, whereas the situation in CH_2Cl_2 was opposite.

The most striking differences between hydroxyl group bearing catalysts and the parent catalysts were obtained in the hydrogenation of ItH_2 and $ItMe_2$. Thus, in the reaction with $ItMe_2$ the hydroxyl group free complexes (**1b**, **2b**, **3c**) gave in the most cases considerably higher selectivities (by up to 16 %*ee*). However, reversed results were obtained when ItH_2 was hydrogenated. Here, thanks to the hydroxyl group improvements by up to 17 %*ee* were achieved.[29]

In order to assess the importance of the spatial orientation of the hydroxyl group to the observed effects the results obtained with the ligands of type **3** are worth investigating. It is obvious that in the hydrogenation of ItH_2 and $ItMe_2$ the different selectivities are confined to **3a**. The catalyst based on **3b** displayed in most cases the same selectivity as **3c.** These results show that contingent on the chosen substrates (for AH and AMe this tendency could not be observed) the spatial orientation of the hydroxyl group to the stereoselectivity of the hydrogenation is of some importance.

Conclusion

In summary, hydroxyl analogues of the optically active DIOP rhodium catalyst were synthesized by two different pathways in good yields. The applicability of these complexes for the hydrogenation of various prochiral olefins was proven in comparison with parent Rh catalysts which do not bear a hydroxyl group. In methanol pronounced effects which might be attributed to the remote hydroxyl group were sparsely observed. However, a remarkable change of the enantiodifferentiating properties of the applied complexes was found when the hydrogenations were carried out in CH_2Cl_2 or toluene. In these less polar solvents those phosphine complexes which possess the hydroxyl group performed superior to those of the nonsubstituted catalysts especially in the hydrogenation of itaconic acid. On the other hand, application of the hydroxyl catalyst to the

reduction of dimethyl itaconate in most cases lowered the %*ee* in comparison to the parent complexes. In general, for each pair of catalysts (hydroxyl catalyst/parent catalyst) an improvement of the selectivity in the hydrogenation of a substrate acid caused by the hydroxyl group is contrasted with an inferior selectivity for the corresponding ester or vice versa, respectively. The directed influence of the hydroxyl group could be evidenced in the comparison of the catalysts based on the ligand bearing the o- or p-phenol moiety, respectively. It is suggestive to assume, that in the case of hydroxyl group bearing catalysts presented above through space interactions (attractive or repulsive) between the properly oriented remote functional group and parts of the substrates (e.g the α-carboxylic group in itaconic acid) can influence the selectivity of the metal catalyst.[30,31] However, such effects, which as expected should be small due to the long distance between hydroxyl group and substrate, may be easily overridden by steric grounds residing in the backbone of the ligands. Further work on the utilization of remote functional groups on the fine tuning of selected phosphine catalysts is continuing.

Experimental Section

All dry solvents were distilled under argon. Reactions involving phosphines and organometallic compounds were performed under an Ar atmosphere by using standard Schlenk techniques. Tetrahydrofuran (THF) was purified by distillation from sodium/benzophenone ketyl. Thin-layer chromatography was performed on precoated TLC plates (silica gel 60 F_{254}, Merck). Flash chromatography was carried out with silica gel 60 (particle size 0.040 - 0.063 mm, Merck). Melting points are corrected. Optical rotations were measured on a "gyromat-HP" (Firma Dr. Kernchen). IR spectra were measured on a Nicolet Magna - IR 550 instrument. NMR spectra were recorded on a Bruker AC 250 instrument at 303 K. Spectra were obtained at the following frequencies: 250.13 MHz (^{1}H), 62.90 MHz (^{13}C), 101.26 MHz (^{31}P). Chemical shifts of ^{1}H and ^{13}C NMR spectra are reported in ppm downfield from TMS as internal standard. Chemical shifts of ^{31}P NMR spectra are reported in ppm referred to H_3PO_4 as external standard. The mass spectra were recorded on an AMD 402 instrument (Firma Intectra) at an ionization voltage of 70 eV.

(*S,S*)-2,3-Bis(O-trimethylsilyl)-1,4-bis[O-(p-toluenesulfonyl)]butane-1,2,3,4-tetrol (5). To a solution of 5 g (11.6 mmol) of (*S,S*)-1,4-di-O-tosylbutane-1,2,3,4-tetrol (**4**)[14] in 10 mL of dry CH_2Cl_2 1.0 mL (7.74 mmol) of trimethylsilyl chloride (TMSCl) and 1.65 mL (7.74 mmol) of hexamethyl disilazane (HMDS) was added dropwise at room temperature. After stirring overnight the solution was filtered over silica gel to remove the formed NH_4Cl. The CH_2Cl_2 was distilled under reduced pressure and the residue subjected to flash chromatography (*n*-hexane/ethyl acetate 2/1) to give the silyl derivative **5** as a colourless oil (5.50 g, 82 %): $[\alpha]_D^{25}$ = -14.4 (*c* 1.4, $CHCl_3$); IR (neat) 3067, 3034, 2958, 2927, 2900, 1599, 1495, 1453, 1401, 1368, 1256, 1190, 1180, 1122, 1099, 989, 952, 815, 753, 706, 666, 571, 555 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.78 - 7.72 (m, 4 arom. H), 7.32 - 7.26 (m, 4 arom. H), 4.10 - 4.02 (m, 2H), 3.82 - 3.74 (m, 4H), 2.42 (s, 6H), 0.10 (s, 18H); ^{13}C NMR ($CDCl_3$) δ 144.9, 132.9, 129.8, 127.9, 71.2, 70.0, 21.6, -0.1; MS *m/e* 574 (M^+, 0.1), 559 (M^+ - CH_3, 0.3), 531 (2), 473 (3), 317 (73), 229 (51), 165 (25), 155 ($C_7H_7SO_2^+$, 18), 116 (45), 91 ($C_7H_7^+$,

28), 73 ($(CH_3)_3Si^+$, 88), 43 (CH_3Si^+, 100). Anal. calc. for $C_{24}H_{38}O_8S_2Si_2$ (574.9): C, 50.15; H, 6.66. Found: C, 50.33; H, 6.75.

General Procedure for the Acetalization of 5. 4.5 g (7.82 mmol) of the silyl derivative **5** and 7.82 mmol of ketones **6a-e** were dissolved in 5 mL of $CHCl_3$. 25 mL of trimethylsilyl triflate (TMSOTf) were added at room temperature and the mixture was stirred overnight.[32] The dark red solution obtained was diluted with 10 mL of $CHCl_3$ and poured into 75 mL of a 5 % aqueous solution of K_2CO_3. The water was extracted with CH_2Cl_2 (3 x 25 mL). The organic phase was dried (Na_2SO_4), filtered and evaporated to give the acetals **7a-e**, which were purified by flash chromatography.

(*S,S*)-2-(Acetoxymethyl)-2-phenyl-4,5-bis(p-toluenesulfonyloxymethyl)-1,3-dioxolane (7a). The reaction of **5** with acetic acid-2-oxo-2-phenylethylester (**6a**) (1.31 g, 7.82 mmol) gave **7a** as a white solid (2.77 g, 60 %): mp 79 - 80 °C; $[\alpha]_D^{21}$ = +1.3 (*c* 1.5, $CHCl_3$); IR (KBr) 3064, 3031, 2954, 2927, 1744, 1598, 1494, 1450, 1364, 1241, 1178, 1096, 981, 816, 762, 705, 666, 555 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.86 - 7.27 (m, 13 arom. H), 4.30 - 4.02 (m, 5H), 3.86 (m, 2H), 3.80 (dd, 1H, *J* = 10.8, 5.6 Hz), 2.43 (s, 6H), 2.01 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 170.1, 145.3, 145.2, 138.8, 132.5 - 125.7, 109.7, 76.4, 76.0, 68.0, 67.9, 66.9, 21.6, 20.6; MS *m/e* 591 (M^+ + 1, 3), 517 (M^+ - CH_3COOCH_2, 98), 363 (517 -TsOH, 7), 191 (363 - TsOH, 18), 155 ($C_7H_7SO_2^+$, 96), 105 ($PhCO^-$, 99), 91 ($C_7H_7^+$, 100), 43 (CH_3CO^+, 63). Anal. calc. for $C_{28}H_{30}O_{10}S_2$ (590.6): C, 56.94; H, 5.12; S 10.86. Found: C, 56.96, H, 5.25; S, 10.85.

(*S,S*)-2-Methyl-2-phenyl-4,5-bis(p-toluenesulfonyloxymethyl)-1,3-dioxolane (7b). The reaction of **5** with 0.91 mL of acetophenone (7.82 mmol) (**6b**) gave **7b** as a white solid (3.31 g, 80 %): mp 166 - 169 °C; $[\alpha]_D^{23}$ = -11.0 (*c* 1, $CHCl_3$); IR (KBr) 3066, 3048, 3031, 2996, 2955, 2943, 1598, 1494, 1452, 1358, 1310, 1247, 1191, 1177, 1097, 1060, 966, 873, 840, 815, 773, 709, 667, 570, 558 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.77 - 7.22 (m, 13 arom. H), 4.09 (d, 2H, *J* = 4.6 Hz), 4.02 (m, 1H), 3.81 (dd, 1H, *J* =10.4, 5.8 Hz), 3.73 (m, 1H), 3.60 (dd, 1H, *J* =10.4, 5.8 Hz), 2.39 (s, 6H), 1.47 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 145.2, 145.1, 143.3, 132.7, 132.4, 130.0 - 124.8, 111.0, 76.1, 75.6, 68.7, 68.6, 28.7, 21.7; MS *m/e* 532 (M^+, 0.1), 517 (M^+ - CH_3, 100), 455 (M^- - C_6H_5, 9), 363 (517 -TsOH, 1), 191 (363 - TsOH, 11), 155 ($C_7H_7SO_2^+$, 43), 105 ($PhCO^+$, 99), 91 ($C_7H_7^+$, 70), 77 ($C_6H_5^+$, 10). Anal. calc. for $C_{26}H_{28}O_8S_2$ (532.6): C, 58.63; H, 5.30; S, 12.04. Found: C, 58.37; H, 5.17; S, 11.90.

(*S,S*)-2-(Acetoxymethyl)-2-methyl-4,5-bis(p-toluenesulfonyloxymethyl)-1,3-dioxolane (7c). The reaction of **5** with 0.85 mL (7.82 mmol) of O-acetyl hydroxyacetone (**6c**) gave **7c** as a white solid (3.71 g, 89 %): mp 67 - 68 °C; $[\alpha]_D^{23}$ = -10 (*c* 1, $CHCl_3$); IR (KBr) 3040, 2995, 2959, 2928, 2896, 1744, 1598, 1496, 1457, 1377, 1244, 1173, 1098, 977, 816, 774, 666, 553 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.77 - 7.33 (m, 8 arom. H), 4.09 - 4.00 (m, 6H), 3.90 (d, 1H, *J* = 12.0 Hz), 3.81 (d, 1H, *J* = 12.0 Hz), 2.41 (s, 6H), 1.99 (s, 3H), 1.23 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 170.1, 145.2, 145.1, 132.3, 132.2, 129.9, 127.9, 109.2, 76.0, 75.0, 67.9, 67.8, 66.6, 21.5, 20.6; MS *m/e* 528 (M^+, 0.5), 513 (M^+ - CH_3, 0.7), 455 (M^+ - CH_3COOCH_2, 38), 319 (48), 155 ($C_7H_7SO_2^+$, 95), 89 (98), 45 (100). Anal. calc. for $C_{23}H_{28}O_{10}S_2$ (528.6): C, 52.26; H, 5.34; S, 12.13. Found: C, 52.18; H, 5.42; S, 12.05.

(*S,S*)-2-(2'-Acetoxyphenyl)-4,5-bis(p-toluenesulfonyloxymethyl)-1,3-dioxolane (7d). The reaction of **5** with 1.28 g (7.82 mmol) of O-acetyl salicyl aldehyde (**6d**) gave **7d** as a reddish oil (3.17 g, 70 %): $[\alpha]_D^{23}$ = -16.5 (*c* 1, $CHCl_3$); IR (neat) 3068, 2982, 2954, 2927, 1767, 1598, 1494, 1456, 1364, 1242, 1178, 1095, 981, 816, 787, 762, 666, 555 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.82 - 7.10 (m, 12 arom. H), 6.04 (s, 1H), 4.26 - 4.08 (m, 6H), 2.42 (s, 6H), 1.99 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 169.1, 148.9, 145.4, 145.3, 132.5 - 122.8, 100.5, 75.5, 75.4, 68.3, 68.2, 21.6, 20.8; MS *m/e* 576 (M^+, 2), 534 (M^+ + H-CH_3CO, 27), 533 (M^+ - CH_3CO, 27), 517 (M^+ - CH_3COO, 30), 227 (517 - C_6H_4CHO - $TsOCH_2$, 12), 155 ($C_7H_7SO_2^+$, 97), 121 ($C_6H_5OCO^+$, 31), 91 ($C_7H_7^+$, 100). Anal. calc. for $C_{27}H_{28}O_{10}S_2$ (576.64): C, 56.24, H, 4.89, S, 11.12. Found: C, 56.13; H, 4.98; S, 11.05.

(*S,S*)-2-(4'-Acetoxyphenyl)-4,5-bis(p-toluensulfonyloxymethyl)-1,3-dioxolane (7e). The reaction of **5** with 1.50 g (9.16 mmol) of O-acetyl 4-hydroxybenzaldehyde (**6e**) gave **7e** as a white solid (3.86 g, 73 %): mp 94 °C; $[\alpha]_D^{25}$ = -19.0 (*c* 1.03, $CHCl_3$); IR (neat) 3063, 2958, 2923, 2883, 1776, 1597, 1510, 1452, 1364, 1191, 1178, 1095, 989, 975, 913, 886, 820, 785, 682, 664, 567, 553 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.80 - 7.00 (m, 12 arom. H), 5.76 (s, 1H), 4.21 - 4.09 (m, 6H), 2.41 (s, 3H), 2.40 (s, 3H), 2.28 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 169.0, 151.4, 145.2, 133.6 - 121.3, 103.7, 75.5, 75.1, 68.3, 68.1, 21.4, 20.9; MS *m/e* 576 (M^+, 20), 533 (M^+ - CH_3CO, 28), 517 (M^+ - CH_3COO, 40), 227 (517 -C_6H_4CHO - $TsOCH_2$, 22), 191 (20), 155 ($C_7H_7SO_2^+$, 68), 121 ($C_6H_5OCO^+$, 74), 91 ($C_7H_7^+$, 100). Anal. calc. for $C_{27}H_{28}O_{10}S_2$ (576.64): C, 56.24; H, 4.89; S, 11.12. Found : C, 56.08; H, 4.90; S, 11.00.

(*S,S*)-2-(Hydroxymethyl)-2-phenyl-4,5-bis(p-toluenesulfonyloxymethyl)-1,3-dioxolane (8). A suspension of 1.55 g (2.62 mmol) of the acetate **7a** in 50 mL of methanol was treated with 2.5 mL of a 1 % methanolic solution of NaOMe. The reaction was followed by tlc (*n*-hexane/ethyl acetate 1/1). After completion of the deacetylation (approx. 2 h) the mixture was poured in 100 mL of water. The water was extracted with CH_2Cl_2 (4 x 75 mL). The extract was dried (Na_2SO_4), filtered and evaporated. The residue was subjected to flash chromatography (*n*-hexane/ethyl acetate 1/1) to give the deprotected alcohol **8** as a white solid (1.10 g, 78 %): mp 154 - 155 °C; $[\alpha]_D^{23}$ = -12.5 (*c* 0.5, $CHCl_3$); IR (KBr) 3588, 3069, 2956, 2934, 2887, 1597, 1452, 1351, 1309, 1190, 1175, 1095, 1021, 966, 901, 864, 842, 816, 767, 710, 667, 571, 557 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.87 - 7.26 (m, 13 arom. H), 4.14 (dd, 1H, *J* = 11.2, 3.9 Hz), 4.07 (m, 1H), 4.03 (dd, 1H, *J* = 11.2, 4.8 Hz), 3.78 (m, 1H), 3.74 (dd, 1H, *J* = 10.4, 5.7 Hz), 3.57 (dd, 1H, *J* = 10.4, 6.0 Hz), 3.40 (AB, 2H, *J* = 12.8 Hz), 2.44 (s, 6H), 2.20 (b, OH, exchangeable with D_2O); ^{13}C NMR ($CDCl_3$) δ 145.4, 145.2, 139.4, 132.7 - 125.6, 111.5, 76.3, 76.2, 68.3, 68.0, 67.0, 21.6; MS *m/e* 530 (M^+ - H_2O, 0.3), 517 (M^+ - CH_2OH, 45), 175 (25), 155 ($C_7H_7SO_2^+$, 25), 105 ($PhCO^+$, 100), 91 ($C_7H_7^+$, 47), 77 ($C_6H_5^+$, 18). Anal. calc. for $C_{26}H_{28}O_9S_2$ (548.6): C, 56.92; H, 5.14; S, 11.69. Found : C, 56.72; H, 5.25; S, 11.75.

(4*S*,5*S*,2'*rac*)-2-Phenyl-2-[(tetrahydropyran-2'-yl)oxymethyl]-4,5-bis(p-toluenesulfonyloxymethyl)-1,3-dioxolane (9). To a solution of 2.00 g (3.64 mmol) of the alcohol **8** in 30 mL of dry CH_2Cl_2 were added 100 mg of pyridinium p-toluenesulfonate (PPTS) and 0.5 mL (5.46 mmol) of 3,4-dihydro-2H-pyran. The mixture was stirred for 5 h at room temperature. The solution was diluted with 60 mL of ether and washed twice with half-saturated brine and water. After drying the ether solution (Na_2SO_4) the solvent was evaporated and the residue purified by flash chromatography (*n*-hexane/ethyl acetate 2/1) to furnish the

diastereomeric mixture of the THP ether **9** as a pale yellow oil (2.26 g, 98 %): IR (KBr) 3064, 3018, 2944, 2871, 1598, 1494, 1450, 1365, 1263, 1241, 1190, 1178, 1125, 1097, 1038, 983, 815, 766, 703, 665, 555 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.75 - 7.18 (m, 13 arom. H), 4.47 (m, 1H), 4.27 - 4.18 (m, 3H), 3.90 - 3.81 (m, 2H), 3.78 (m, 1H), 3.71 - 3.57 (m, 2H), 3.43 - 3.28 (m, 2H), 2.39 (s, 6H), 1.75 - 1.30 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 145.2, 145.2, 139.9/138.8, 132.7 - 125.7, 111.3/111.2, 98.7/98.5, 77.2/76.9, 76.0/75.9, 71.1/70.9, 68.7/68.7, 68.5/68.4, 61.7/61.6, 30.2/30.1, 25.3, 21.7, 19.0/18.9; MS *m/e* 516 [M^+ - (THP - OCH_2) - H, 10], 175 [M^+ - (THP - OCH_2) - 2 x OTs, 28], 155 ($C_7H_7SO_2^+$, 12), 105 ($PhCO^+$, 100), 91 ($C_7H_7^+$, 23), 77 ($C_6H_5^+$, 13). Anal. calc. for $C_{31}H_{36}O_{10}S_2$ (632.7): C, 58.85; H, 5.73; S, 10.13. Found : C, 58.93; H, 5.74; S 10.01.

General procedure for the substitution of the tosyl groups with lithium diphenylphosphide. A solution of lithium diphenylphosphide was generated from 165 mg (23.7 mmol) of lithium strips and 1.74 mL (9.48 mmol) of freshly distilled chlorodiphenylphosphine in 10 mL of THF. The resultant deep red solution was added at 0 °C to a solution of 2.37 mmol of the ditosylate in 10 mL of THF over a period of 30 min. The solution was stirred for a further 3 h at room temperature and then the solvent removed. To the residue 15 mL of oxygen free water were added. The suspension was extracted with 30 mL of CH_2Cl_2. The organic extract was dried (Na_2SO_4), filtered and evaporated. The crude bisphosphine was subjected to flash chromatography.

(4*R*,5*R*,2'*rac*)-4,5-Bis(diphenylphosphinomethyl)-2-phenyl-2-[(tetrahydropyran-2'-yl)oxymethyl]-1,3-dioxolane (10). The reaction of 1.50 g of ditosylate **9** with lithium diphenylphosphide gave **10** as a colourless oil (1.10 g, 70 %): IR (neat) 3070, 3054, 3020, 2940, 2870, 1955, 1887, 1813, 1585, 1571, 1481, 1449, 1434, 1387, 1352, 1304, 1261, 1241, 1182, 1125, 1074, 999, 984, 906, 870, 815, 696, 558, 507 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.50 - 7.18 (m, 25 arom. H), 4.47 (m, 1H), 4.15 (m, 1H), 3.81 (m, 1H), 3.67 - 3.50 (m, 2H), 3.42 (m, 1H), 3.27 (m, 1H), 2.39 (m, 2H), 2.22 (m, 2H), 1.75 - 1.25 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 141.3, 138.6-126.1, 109.1, 98.3/98.2, 81.7 (m), 80.4 (m), 71.6/71.4, 61.2/61.3, 32.2 (d, $^1J_{P-C}$ = 15.5 Hz)/32.1 (d, $^1J_{P-C}$ = 15.6 Hz), 31.8 (dd, $^1J_{P-C}$ = 16.2, $^4J_{P-C}$ = 3.1 Hz)/31.6 (dd, $^1J_{P-C}$ = 16.2 Hz, $^4J_{P-C}$ = 2.9 Hz), 30.4/30.3, 25.5, 18.8/18.8; ^{31}P NMR ($CDCl_3$) δ -21.1/-21.3, -21.3/-21.7; MS *m/e* 475 (M^+ - PPh_2, 100), 423 (10), 391 (475 - C_5H_8O, 20), 255 ($C_{16}H_{16}OP^+$, 42), 239 ($C_{16}H_{16}P^+$, 14), 185 (PPh_2^+, 61), 105 ($PhCO^+$, 8), 85 ($C_5H_9O^+$, 11). Anal. calc. for $C_{41}H_{42}O_4P_2$ (660.7): C, 74.53; H, 6.41. Found : C, 74.42; H, 6.22.

(*R*,*R*)-4,5-Bis(diphenylphosphinomethyl)-2-(hydroxymethyl)-2-phenyl-1,3-dioxolane (1a). A solution of the diastereomeric mixture of 0.85 g (1.29 mmol) of THP ether **10** in 30 mL of methanol, 3 mL of water and 40 mL of trifluoroacetic acid was heated under reflux for 3 h. The solution was cooled to room temperature and the solvents removed under reduced pressure. The residue was purified by flash chromatography (*n*-hexane/ethyl acetate 2/1) to yield the hydroxy bisphosphine **1a** as a colourless tough syrup (0.6 g, 81 %): $[\alpha]_D^{21}$ = -30 (*c* 0.8, $CHCl_3$); IR (KBr) 3433, 3052, 2916, 2850, 1481, 1433, 1236, 1153, 1102, 1070, 1053, 1024, 999, 739, 695, 506 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.40 - 7.18 (m, 25 arom. H), 4.12 (m, 1H), 3.86 (m, 1H), 3.46 (s, 2H), 2.49 (ddd, 1H, *J* = 14.0, 5.2, 0.9 Hz), 2.38 (dd, 1H, *J* = 14.0, 6.7 Hz), 2.24 (dd, 1H, *J* = 13.7, 7.3 Hz), 2.08 (dd, 1H, *J* = 13.7, 5.8 Hz), 1.90 (s, 1H, exchangeable with D_2O); ^{13}C NMR ($CDCl_3$) δ 140.8, 138.2 - 125.9, 109.5, 81.8 (dd, $^2J_{P-C}$ = 17.2 Hz, $^3J_{P-C}$ = 8.6 Hz), 80.2 (dd, $^2J_{P-C}$ = 14.3 Hz, $^3J_{P-C}$ = 7.6 Hz), 67.8, 32.6 (d, $^1J_{P-C}$ = 16.2 Hz), 31.8 (d, $^1J_{P-C}$ = 15.3 Hz); ^{31}P NMR ($CDCl_3$)

δ -22.7; MS *m/e* 576 (M^+, 6), 545 (M^+ - CH_2OH, 18), 391 (545 - 2 x C_6H_5, 100), 255 (31), 185 (PPh_2^+, 79), 105 (PPh^+, 8), 77 ($C_6H_5^+$, 8). Anal. calc. for $C_{36}H_{34}O_3P_2$ (576.6): C, 74.99; H, 5.94. Found: C, 74.81; H, 6.12.

(*R,R*)-4,5-Bis(diphenylphosphinomethyl)-2-methyl-2-phenyl-1,3-dioxolane (1b). The reaction of 1.26 g (2.37 mmol) of ditosylate **7b** with lithium diphenylphosphide gave **1b** as a colourless oil (1.0 g, 79 %): $[\alpha]_D^{23}$ = -40.4 (*c* 0.67, $CHCl_3$); IR (neat) 3070, 3054, 3028, 2986, 2931, 2902, 2874, 1955, 1888, 1814, 1585, 1481, 1434, 1371, 1309, 1261, 1204, 1094, 1025, 985, 915, 890, 805, 765, 740, 696, 594 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.45 - 7.10 (m, 25 arom. H), 3.96 (m, 1H), 3.69 (m, 1H), 2.38 (m, 2H), 2.13 (dd, 1H, *J* = 13.9, 7.8 Hz), 2.04 (dd, 1H, *J* = 13.9, 5.7 Hz), 1.49 (s, 3H); ^{13}C NMR ($CDCl_3$): 144.9, 138.3 - 125.2, 109.0, 80.8 (dd, $^2J_{P-C}$ = 14.3 Hz, $^3J_{P-C}$ = 7.6 Hz), 80.2 (dd, $^2J_{P-C}$ = 16.2 Hz, $^3J_{P-C}$ = 7.6 Hz), 32.5 (dd, $^1J_{P-C}$ = 15.2 Hz, $^4J_{P-C}$ = 1.9 Hz), 32.0 (dd, $^1J_{P-C}$ = 16.2 Hz, $^4J_{P-C}$ = 3.8 Hz), 29.2; ^{31}P NMR ($CDCl_3$) δ -21.6, -21.8; MS *m/e* 483 (M^+ - Ph, 3), 375 (M^+ - PPh_2, 100), 255 (375 - $PhCOCH_3$, 76), 185 (PPh_2^+, 90). Anal. calc. for $C_{36}H_{34}O_2P_2$ (560.6): C, 77.12; H, 6.11. Found: C, 77.19; H, 6.03.

(*R,R*)-4,5-Bis(diphenylphosphinomethyl)-2-(hydroxymethyl)-2-methyl-1,3-dioxolane (2a). The reaction of 1.25 g (2.36 mmol) of ditosylate **7c** with lithium diphenylphosphide gave the crude phosphine that was separated from **11** which has been formed as by-product by flash chromatography (*n*-hexane/ethyl acetate 4/1) to give **2a** as a colourless oil (0.63 g, 52 %): $[\alpha]_D^{23}$ = -22.6 (*c* 0.62, $CHCl_3$); IR (neat) 3431, 3070, 3053, 2980, 2934, 2871, 1957, 1886, 1814, 1585, 1481, 1434, 1375, 1306, 1246, 1159, 1092, 1067, 1027, 999, 891, 741, 697, 507 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.47 - 7.30 (m, 20 arom. H), 3.98 (m, 2H), 3.35 (1H, *J* = 11.7 Hz), 3.31 (1H, *J* = 11.7 Hz), 2.43 (ddd, 1H, *J* = 14.0, 4.9, 1.7 Hz), 2.29 (dd, 2H, *J* = 5.8, 1.6 Hz), 2.25 (dd, 1H, *J* = 14.0, 6.4 Hz), 1.78 (s, 1H, exchangeable with D_2O), 1.21 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 138.4 - 128.4, 109.1, 80.5 (dd, $^2J_{P-C}$ = 15.3 Hz, $^3J_{P-C}$ = 8.7 Hz), 79.7 (dd, $^2J_{P-C}$ = 13.5 Hz, $^3J_{P-C}$ = 7.5 Hz), 67.4, 31.7 (dd, $^1J_{P-C}$ = 14.5 Hz, $^4J_{P-C}$ = 3.6 Hz), 31.7 (dd, $^1J_{P-C}$ = 16.0 Hz, $^4J_{P-C}$ = 2.2 Hz), 22.7; ^{31}P NMR ($CDCl_3$) δ -23.1, -23.4; MS *m/e* 514 (M^+, 2), 483 (M^+ - CH_2OH, 14), 437 (M^+ - C_6H_5, 5), 329 (M^+ - PPh_2, 62), 255 (26), 185 (PPh_2^+, 100). Anal. calc. for $C_{31}H_{32}O_3P_2$ (514.6): C, 72.36; H, 6.27. Found: C, 72.23; H, 6.31.

(*R,R*)-4,5-Bis(diphenylphosphino)-2-(2'-hydroxyphenyl)-1,3-dioxolane (3a). The reaction of 1.37 g (2.38 mmol) of ditosylate **7d** with lithium diphenylphosphide gave the crude phosphine which was isolated by flash chromatography (*n*-hexane/ethyl acetate 9/1) to give **3a** as a colourless oil (1.0 g, 76 %); $[\alpha]_D^{26}$ = -20.5 (*c* 0.67, $CHCl_3$); IR (neat) 3411, 3070, 3053, 2980, 2926, 2871, 1957, 1886, 1814, 1620, 1586, 1482, 1434, 1369, 1300, 1253, 1181, 1153, 1092, 1067, 1029, 999, 937, 740, 696, 507 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.47 - 6.72 (m, 24 arom. H), 5.95 (s, 1H), 4.12 (m, 2H), 2.40 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 155.2, 137.8 - 117.2, 103.3, 81.5 (dd, $^2J_{P-C}$ = 17.2 Hz, $^3J_{P-C}$ = 7.6 Hz), 80.0 (dd, $^2J_{P-C}$ = 16.2 Hz, $^3J_{P-C}$ = 7.6 Hz), 32.7 (dd, $^1J_{P-C}$ = 16.2 Hz, $^4J_{P-C}$ = 2.9 Hz), 32.5 (dd, $^1J_{P-C}$ = 16.2 Hz, $^4J_{P-C}$ = 2.9 Hz); ^{31}P NMR ($CDCl_3$) δ -22.8, -23.6; MS *m/e* 562 (M^+, 1), 485 (M^+ - Ph, 11), 377 (M^+ - PPh_2, 70), 255 (377 - HOPhCHO, 100), 185 (PPh_2^+, 56). Anal. calc. for $C_{35}H_{32}O_3P_2$ (562.6): C, 74.72; H, 5.73. Found : C, 74.61; H, 5.50.

(*R*,*R*)-4,5-Bis(diphenylphosphino)-2-(4'-hydroxyphenyl)-1,3-dioxolane (3b). The reaction of 1.50 g (2.60 mmol) of ditosylate **7e** with lithium diphenylphosphide gave the crude phosphine, which was isolated by flash chromatography (*n*-hexane/ethyl acetate 9/1) to give **3b** as a colourless oil (1.23 g, 82 %); $[\alpha]_D^{26}$ = -1.0 (*c* 0.69, $CHCl_3$); IR (neat) 3399, 3069, 3050, 3027, 3001, 2897, 1616, 1599, 1505, 1481, 1433, 1400, 1370, 1330, 1301, 1265, 1217, 1166, 1068, 1026, 999, 835, 739, 695, 582, 507 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.48 - 7.16 (m, 22 arom. H), 6.70 (m, 2 arom. H), 5.84 (s, 1H), 5.50 (b, 1H, exchangeable with D_2O), 4.17 (m, 2H), 2.57 - 2.42 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 156.4, 138.0, 133.0 - 128.2, 115.0, 102.8, 81.3 (dd, $^2J_{P-C}$ = 16.6 Hz, $^3J_{P-C}$ = 7.5 Hz), 79.8 (dd, $^2J_{P-C}$ = 16.1 Hz, $^3J_{P-C}$ = 8.0 Hz), 32.9 (dd, $^1J_{P-C}$ = 15.7 Hz, $^4J_{P-C}$ = 2.8 Hz), 32.8 (dd, $^1J_{P-C}$ = 15.3 Hz, $^4J_{P-C}$ = 1.9 Hz); ^{31}P NMR ($CDCl_3$) δ -22.6, -24.1; MS *m/e* 562 (M^+, 2), 485 (M^+ - Ph, 3), 453 (1), 425 ($M^+ + H - O_2CHC_6H_4OH$, 3), 377 ($M^+ - PPh_2$, 95), 255 ($C_{16}H_{16}OP^+$, 100), 239 ($C_{16}H_{16}P^+$, 48), 185 (PPh_2^+, 89), 108 (PPh^+, 18). Anal. calc. for $C_{35}H_{32}O_3P_2$ (562.6): C, 74.72; H, 5.73. Found: C, 74.61; H, 5.50.

(1*S*,5*S*,7*R*)-7-(Diphenylphosphinomethyl)-5-methyl-3,6,8-trioxabicyclo[3.2.1]octane (11). The compound was isolated as a by-product from the synthesis of the bisphosphine **2a** as a colourless oil (340 mg, 43 %): $[\alpha]_D^{24}$ = -24.5 (*c* 0.85, $CHCl_3$); IR (neat) 3071, 3053, 2987, 2962, 2937, 2854, 1958, 1889, 1814, 1586, 1482, 1434, 1394, 1379, 1325, 1259, 1238, 1206, 1134, 1114, 1081, 1059, 1034, 991, 973 , 864, 741, 697, 669, 509 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.46 - 7.25 (m, 10 arom. H), 4.38 (m, 1H), 4.08 (s, 1H), 3.66 (dd, 1H, *J* = 11.2, 1.2 Hz), 3.41 (dd, 1H, *J* = 11.2, 1.2 Hz), 3.39 (d, 1H, *J* = 11.2 Hz), 3.35 (d, 1H, *J* = 11.2 Hz), 2.45 (ddd, 1H, *J* = 13.6, 5.2, 1.6 Hz), 2.18 (ddd, 1H, *J* = 13.6, 9.2, 1.6 Hz), 1.24 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 138.2 - 128.5, 105.8, 79.9 (d, $^2J_{P-C}$ = 21.0 Hz), 78.8 (d, $^3J_{P-C}$ = 7.6 Hz), 72.2, 67.9, 35.0 (d, $^1J_{P-C}$ = 14.3 Hz), 19.9; ^{31}P NMR ($CDCl_3$) δ -22.6; MS *m/e* 328 (M^+, 100), 285 ($M^+ - CH_3CO$, 8), 269 (50), 239 (269 - CH_2O, 86), 185 (PPh_2^+, 47), 108 (PPh^+, 29), 43 (CH_3CO^+, 57). Anal. calc. for $C_{19}H_{21}O_3P$ (328.3): C, 69.50; H, 6.44. Found: C, 69.12; H, 6.21.

General procedure for the preparation of the Rh complexes. To a stirred solution of the bisphosphine (1 mmol) in 2 mL of THF 311 mg (1 mmol) of Rh(COD)acac were added. The resultant mixture was stirred over a period of 5 min. To the reddish solution a stoichiometric amount of aqueous 40 % HBF_4 was added. The solution was stirred for further 10 min and then the complex was precipitated with 8 mL of ether. The yellow complexes were isolated by filtration and washed several times with ether. The Rh complexes so obtained were spectroscopically unambigeously identified. However, due to the presence of included nonstoichiometric amounts of THF the elemental analysis gave occasionally values beyond the limit of ± 0.4 %.

[Rh(COD)(**1a**)]BF_4. IR (KBr) 3540, 3058, 2954, 2929, 2880, 2836, 1483, 1435, 1315, 1254, 1182, 1085, 1055, 999, 903, 819, 744, 701, 512 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.80 - 7.16 (m, 25 arom. H), 4.60 - 4.18 (m, 4H), 3.54 (m, 1H), 3.38 (m, 1H), 3.04 - 2.83 (m, 3H), 2.60 - 2.00 (m, 12H); ^{13}C NMR ($CDCl_3$) δ 139.9, 133.7 - 125.3, 109.7, 101.8 (dd, *J* = 7.3, 7.4 Hz), 100.8 (dd, *J* = 8.6, 8.6 Hz), 100.5 (dd, *J* = 7.7, 7.7 Hz), 99.7 (dd, *J* = 7.6, 7.6 Hz), 78.6 (dd, $^2J_{P-C}$ = 9.5 Hz, $^3J_{P-C}$ = 4.8 Hz), 77.5 (m), 67.3, 31.7, 31.6, 31.3, 31.2, 30.9 (d, $^1J_{P-C}$ = 12.4 Hz), 29.7 (d, $^1J_{P-C}$ = 9.5 Hz); ^{31}P NMR ($CDCl_3$) δ 13.7 (dd, $^1J_{Rh-P}$ = 144.0 Hz,

$^2J_{P-P}$ = 36.6 Hz), 13.2 (dd, $^1J_{Rh-P}$ = 143.8 Hz, $^2J_{P-P}$ = 36.6 Hz); MS *m/e* 787 (M^+ - BF_4, 47). $C_{44}H_{46}O_3BF_4P_2Rh$ (874.5).

[Rh(COD)(**1b**)]BF_4. IR (Polychlortrifluorethylene) 3064, 2967, 2928, 2876, 2835, 1483, 1435, 1417, 1376, 1345; ^1H NMR ($CDCl_3$) δ 7.90 - 7.00 (m, 25 arom. H), 4.60 - 4.20 (m, 4H), 3.77 (m, 1H), 3.35 (m, 1H), 3.00 - 2.00 (m, 12H), 1.27 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 143.3, 134.2-124.3, 109.4, 102.6 (dd, *J* = 8.0, 8.0 Hz), 102.4 (dd, *J* = 8.0, 8.0 Hz), 99.8 (dd, *J* = 9.0, 8.0 Hz), 99.5 (dd, *J* = 8.0, 8.0 Hz), 77.3 (m), 76.9 (m), 32.2, 31.9, 31.2 (m), 31.0, 30.7, 39.5 (m, $^1J_{P-C}$ = 12.4 Hz), 28.1; ^{31}P NMR ($CDCl_3$) δ 14.3 (dd, $^1J_{Rh-P}$ = 145.0 Hz, $^2J_{P-P}$ = 36.6 Hz), 13.0 (dd, $^1J_{Rh-P}$ = 145.0 Hz, $^2J_{P-P}$ = 36.6 Hz); *m/e* 772 (M^+ - HBF_4, 4). $C_{44}H_{46}O_2BF_4P_2Rh$ (858.5).

[Rh(COD)(**2a**)]BF_4. IR (KBr) 3442, 3056, 2982, 2921, 2875, 2832, 1483, 1435, 1378, 1315, 1245, 1161, 1124, 1084, 1064, 998, 887, 744, 698, 532, 507 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.80 - 7.32 (m, 20 arom. H), 4.65 - 4.21 (m, 4H), 4.08 (m, 1H), 3.75 (m, 1H), 3.16 (s, 2H), 2.80 (m, 3H), 2.60 - 2.00 (m, 10H), 1.10 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 133.7 - 129.2, 109.4, 101.2 (dd, *J* = 8.3, 8.1 Hz), 100.8 (dd, *J* = 8.3, 8.3 Hz), 100.5 (m), 77.6 (dd, $^2J_{P-C}$ =11.6 Hz, $^3J_{P-C}$ = 4.0 Hz), 77.0 (dd, $^2J_{P-C}$ = 9.4 Hz, $^3J_{P-C}$ = 3.0 Hz), 66.7, 31.5 (d, $^1J_{P-C}$ = 15.0 Hz), 31.3, 30.9, 30.5, 30.2, 30.1 (d, $^1J_{P-C}$ = 9.0 Hz), 22.1; ^{31}P NMR ($CDCl_3$) δ 13.5 (dd, $^1J_{Rh-P}$ = 144.8 Hz, $^2J_{P-P}$ = 36.6 Hz), 12.3 (dd, $^1J_{Rh-P}$ = 144.6 Hz, $^2J_{P-P}$ = 36.6 Hz); MS *m/e* 725 (M^+ - BF_4, 35). $C_{39}H_{44}O_3BF_4P_2Rh$ (812.4).

[Rh(COD)(**3a**)]BF_4. IR (Polychlortrifluorethylene) 3423, 3053, 2968, 2922, 2879, 2834, 1480, 1460, 1435 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.00 - 6.66 (m, 24 arom. H), 5.86 (s, 1H), 4.58-4.23 (m, 4H), 4.00 - 3.70 (m, 2H), 2.97 - 2.75 (m, 3H), 2.58 - 2.05 (m, 10H); ^{13}C NMR ($CDCl_3$) δ 154.8, 134.3 - 127.6, 121.6, 119.7, 117.0, 103.3, 102.3 (m), 101.9 (m), 99.9 (m), 77.3 (m), 76.8 (m), 32.5 -29.0 (m); ^{31}P NMR ($CDCl_3$) δ 14.0 (dd, $^1J_{Rh-P}$ = 145.0 Hz, $^2J_{P-P}$ = 36.6 Hz), 13.0 (dd, $^1J_{Rh-P}$ = 145.0 Hz, $^2J_{P-P}$ = 36.6 Hz); MS *m/e* 774 (M^+ + HBF_4, **18**). $C_{43}H_{44}O_3BF_4P_2Rh$ (860.5).

[Rh(COD)(**3b**)]BF_4. IR (Polychlortrifluorethylene) 3424, 3053, 2968, 2920, 2881, 2833, 1599, 1520, 1480, 1435 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.90 - 6.74 (m, 24 arom. H), 5.42 (s, 1H), 4.55 - 4.25 (m, 4H), 3.67 (m, 2H), 2.96 (m, 1H), 2.84 (m, 1H), 2.69 (m, 1H), 2.50 - 2.01 (m, 9H); ^{13}C NMR ($CDCl_3$) δ 157.7, 135.7 - 127.6, 115.4, 102.4, 99.7 (m), 99.4 (m), 78.4 (m), 77.2 (m), 31.2 (m); ^{31}P NMR ($CDCl_3$) δ 13.8 (dd, $^1J_{Rh-P}$ = 145.8 Hz, $^2J_{P-P}$ = 37.3 Hz), 13.5 (dd, $^1J_{Rh-P}$ = 144.2 Hz, $^2J_{P-P}$ = 37.3 Hz); MS *m/e* 773 (M^+ - BF_4, 55). $C_{43}H_{44}O_3BF_4P_2Rh$ (860.5).

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18. It is noteworthy that by prolonged treatment with the acid the cyclic acetal was cleaved.
19. A similar result was observed with hydroxy norphos (ref. 3a), wherein an intramolecular hydrogen bond (ν_{OH} = 3405 cm^{-1}) between the two *endo* functional groups (OH and PPh_2) was cleaved as a result of complex formation with rhodium (ν_{OH} = 3526 cm^{-1}). (Börner, A.; Ward, J.; Tillack, A.; Kagan, H. B. unpublished results.) We observed OH bands in chelating hydroxyalkylphosphine rhodium complexes at 3217 cm^{-1}. (ref. 7b).
20. However, it should be taken into consideration that a reliable estimation of the "true activities" of the catalysts for the substrate hydrogenation cannot be derived from the values given in the table. Because the measured time involves also that period which is necessary to produce the catalyst from the precatalyst by hydrogenation of COD. (Heller, D.; Kortus, K.; Selke, R. *Liebigs Ann.* **1995**, 575.)
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26. The addition of equimolar amounts of triethylamine during the hydrogenation of substrate acids in methanol caused for all catalysts a prolongation of the hydrogenation time. Simultaneously, for AH the enantioselectivies decreased within a range of 5 -10 %*ee*. In case of ItH_2 the %*ee* increased slightly (1 - 3 %*ee*).
27. Monitoring a reaction indicated that in some cases the hydrogen consumption increased with increasing conversion of the substrate. When further substrate was added after the completion of the hydrogenation a remarkable decrease of the hydrogenation time was observed, which can be rationalized by the better solubility of the catalytically active species in toluene.

28. It is necessary to remark that for the other catalysts the results obtained in the hydrogenation of ItH_2 in toluene varied over repeated runs within a limit of 3 %*ee*. This behaviour is likely due to the low solubility of this substrate in toluene.
29. In the same hydrogenation with a rhodium-DiPAMP catalyst low optical yield was obtained, because of the tendency of ItH_2 to form dimers. In order to cleave the hydrogen bridge the reaction mixture was diluted. (Christopfel, W. C.; Vineyard, B. D. *J. Am. Chem. Soc.* **1979**, *101*, 4406). The application of a ruthenium catalyst was similarly successful to prevent dimerisation of ItH_2 (Kawano, H.; Ishii, Y.; Ikariya, T.; Saburi, M.; Yoshikawa, S.; Uchida, Y.; Kumobayashi, H. *Tetrahedron Lett.* **1987**, *28*, 1905).
30. A similar influence has been suggested to rationalize the results obtained for the pressure hydrogenation of ketones with a rhodium complex containing the chiral hydroxyalkylferrocenyl-phosphine (*R*)-(*S*)-BPPFOH: ref. 3b.
31. However, hydrogen bonding between the hydroxyl group and one oxygen of the dioxolane cycle during the catalytic cycle, as excluded for the precatalysts, cannot be ruled out. Such an interaction should also change the steric properties of the chirality inducing backbone.
32. In some attempts the addition of a few drops of $HClO_4$ was revealed to be advantageous to achieve a rapid reaction.

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