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Towards chiral non-racemic *cis*-1,3-disubstituted cyclopentane 1,4-diphosphines

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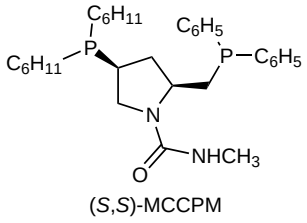
Abstract—Reaction of dialkyl- or diaryl-*trans*-(3,4-epoxycyclopentyl)phosphine oxides **2** with the lithium derivative of methyldiphenylphosphine oxide gives a mixture of (±)-*t*-4- and (±)-*c*-4-(disubstituted phosphinoyl)-*t*-2-(diphenylphosphinoylmethyl)-*r*-1-cyclopentanol derivatives **13a–c** and **16a–c**, which could be obtained in pure form by separation of the corresponding acetates **14a–c** and **17a–c** followed by methanolysis. Compounds **13b** and **16b** were transformed into the corresponding dehydroxy derivatives **19** and **21** through the Barton procedure. Additionally, **16a** was transformed into a diastereomeric mixture of carbamates **22** and **23** on reaction with (*S*)-α-phenylethylisocyanate which could be separated by repeated crystallization. The relative configuration of compounds **13b**, **17a**, **21** and **22** was established by X-ray diffraction analysis.

1. Introduction

Chiral diphosphines have been extensively used as ligands for transition metals in catalytic asymmetric processes,[1] of interest for the synthesis of enantiopure drugs.[2] Among them, *cis*-1,4-diphosphines derived from (2*S*,4*R*)-4-hydroxyproline, containing a five-membered pyrrolidine ring, such as (2*S*,4*S*)-4-(dicyclohexylphosphino)-2-[(diphenylphosphino)methyl]-1-(methylaminocarbonyl)pyrrolidine [(*S*,*S*)-MCCPM][3] (Fig. 1) and its enantiomer [(*R*,*R*)-MCCPM][4] give Rh(I) complexes which perform highly enantioselective reductions of α- and β-amino ketones of interest in connection with the synthesis of drugs such as (*S*)-levamisol,[5] (*S*)-propranolol,[6] the stereoisomers of epronizol,[7] and (*R*)-fluoxetine,[8] among others. However, the industrial application of these diphosphines is greatly conditioned by their lengthy syntheses [15 steps for (*S*,*S*)-MCCPM[3] and 17 steps for (*R*,*R*)-MCCPM,[4] in both cases starting from (2*S*,4*R*)-4-hydroxyproline]. Consequently, the synthesis of analogs of (*S*,*S*)- and (*R*,*R*)-MCCPM through shorter synthetic sequences is of great interest.



(*S*,*S*)-MCCPM

Figure 1. Structure of (*S*,*S*)-MCCPM.

Taking into account that lithiated alkyldiphenylphosphine oxides react with epoxides to give γ-(hydroxyalkyl)phosphine oxides in good yields,[9] and that chlorodisubstituted phosphines react with α,β-unsaturated carbonyl compounds in very good yields,[10] we planned the synthesis of cyclopentane diphosphines, analogs of MCCPM, through the retrosynthetic analysis shown in Fig. 2.

Herein we describe a synthesis of (±)-*t*-4-(disubstituted phosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol derivatives **16a–c** and the dehydroxylated derivative **21**, as well as the enantiomerically pure carbamates **22** and **23** derived from alcohol **16a** and (*S*)-α-

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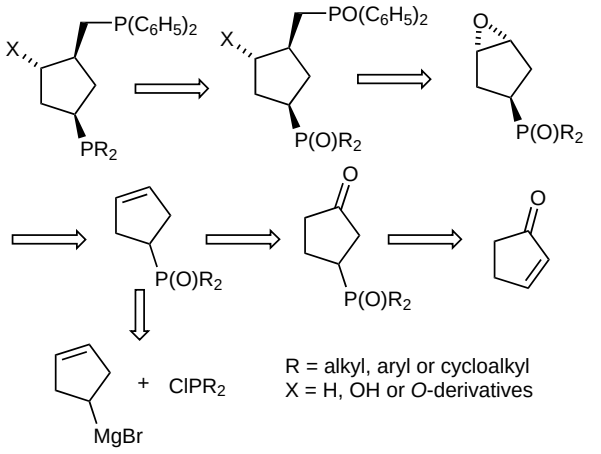
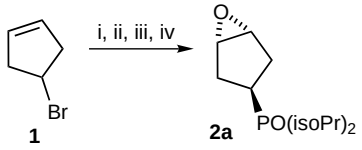


Figure 2. Retrosynthetic analysis to MCCPM analogs.

phenylethylisocyanate, as precursors of the title diphosphines.

2. Results and discussion

The synthesis of compounds **16a–c** involved reaction of epoxides **2** with the lithium derivative of methyldiphenylphosphine oxide as shown in Fig. 2. Firstly, we prepared epoxide **2a** starting from the known 3-cyclopentenyl bromide[11] **1** (Scheme 1). As described, cyclopentadiene[12] was submitted to hydroboration followed by hydrogen peroxide oxidation to give the desired 3-cyclopentenol in 31% yield, somewhat higher than that described in the literature.[11] However, the product was contaminated (^{1}H and ^{13}C NMR) with

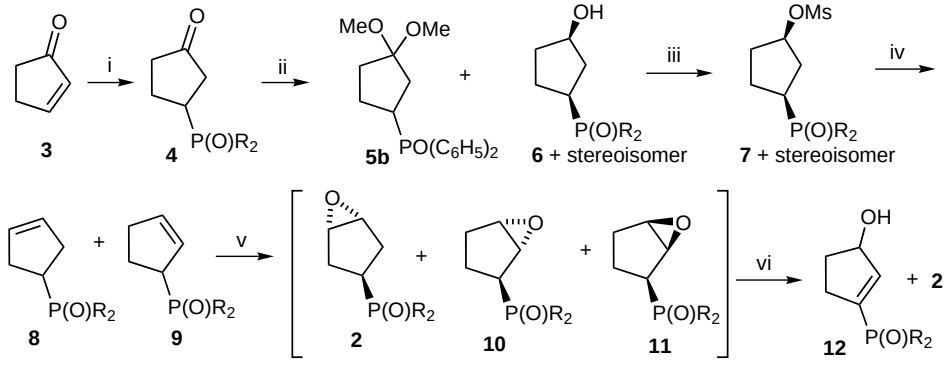


Scheme 1. Preparation of epoxide **2a**. *Reagents and conditions*: (i) Mg, anh. THF; (ii) $ClP(i\text{-}Pr)_2$; (iii) air; (iv) *m*-chloroperbenzoic acid, CH_2Cl_2.

cyclopentanol (probably derived from cyclopentadiene by hydroboration/protonolysis plus hydroboration/oxidation) and *n*-butanol (probably formed by borane reduction of THF). This mixture could not be separated by distillation and was reacted directly with phosphorus tribromide in pentane to give impure 3-cyclopentenyl bromide **1** in about 70% yield.

Reaction of impure **1** (2.5 equiv.) with magnesium turnings in anhydrous THF followed by treatment of the thus formed organomagnesium reagent with chlorodiisopropylphosphine (1 equiv.) and atmospheric oxidation during the work-up gave a mixture the main components of which were 3-cyclopentenyldiisopropylphosphine oxide, cyclopentyldiisopropylphosphine oxide and *n*-butyldiisopropylphosphine oxide (59, 12 and 26% relative areas by GC/MS). This mixture could neither be separated by distillation nor by column chromatography (neutral aluminum oxide) and was reacted as such with *m*-chloroperbenzoic acid (*m*-CPBA) in CH_2Cl_2 to give impure **2a**, which was purified by flash silica gel column chromatography. Although the yield of **2a** from chlorodiisopropylphosphine was only about 10%, we could prepare enough material in this way to carry out the next reactions.

Taking into account the low yield in the preparation of **2a**, compounds **2b** and **2c** were prepared by the alternative route shown in Scheme 2. Reaction of 2-cyclopentenone **3** with chlorodiphenylphosphine in glacial acetic acid afforded 3-diphenylphosphorylcyclopentanone[10] **4b** in 99% yield. $NaBH_4$ reduction of this compound in methanol gave a mixture of *cis*-3-(diphenylphosphoryl)cyclopentanol **6b** and the corresponding *trans*-diastereomer in an approximate ratio of 6:1 (96% yield), from which pure **6b** was isolated by crystallization. Curiously, in one case, a compound that was characterized as the dimethyl acetal of **4b** (compound **5b**) was obtained as the main product from the above reaction. Since formation of acetal **5b** from **4b** requires acid catalysis, formation of **5b** was avoided by carrying out the reduction of **4b** in methanol pre-treated with $NaBH_4$ to destroy possible traces of acid. Mesylation of a mixture of **6b** and its *trans*-stereoisomer gave the corresponding mixture of mesylates in high yield, from



2b, **4b** and **6b-12b**, R = C_6H_5; **2c**, **4c** and **6c-12c**, R = cyclopentyl

Scheme 2. Preparation of epoxides **2**. *Reagents and conditions*: (i) $ClPR_2$, AcOH, 4 Å molecular sieves, rt, 2 h; (ii) $NaBH_4$, MeOH; (iii) MsCl, Et_3N, DMAP (10% M), CH_2Cl_2; (iv) pyrolysis; (v) *m*-chloroperbenzoic acid, CH_2Cl_2; (vi) KOH, EtOH.

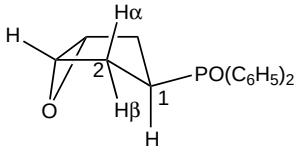
which pure *cis*-mesylate **7b** could be isolated by crystallization. Pyrolysis of the above mixture of **7b** and its *trans*-stereoisomer gave a high yield of a mixture of alkenes **8b** and **9b** in a ratio of ca. 1.8:1, which could not be separated by column chromatography and was characterized 'as is'. Compound **9b** has been prepared previously by our group through a different route.[13] Additionally, we knew[13] that on epoxidation **9b** gives a mixture of epoxides **10b** and **11b**, which on reaction with ethanolic KOH are transformed into the allylic alcohol **12b**. Consequently, to obtain epoxide **2b**, we reacted the mixture of alkenes **8b** and **9b** with *m*-CPBA and the mixture of epoxides **2b**, **10b** and **11b**, thus obtained, was treated with ethanolic KOH to give a mixture of epoxide **2b** and allylic alcohol **12b**, which was easily separated by silica gel column chromatography. In this way, epoxide **2b** was obtained in 26% overall yield from 2-cyclopentenone **3**. Alcohol **12b** was also isolated in 20% overall yield from **3**. The use of alcohols **12** for the synthesis of precursors of 1,3-diphosphines was described recently.[13]

Having developed an efficient access to epoxide **2b**, we then applied a similar procedure to prepare the dicyclopentyl analog **2c**. In this case, the starting chlorodicyclopentylphosphine was prepared as described, by reaction of cyclopentylmagnesium chloride with PCl_3 in the appropriate ratio.[14] Compound **4c** and the mixtures of **6c** and **7c** and their *trans*-stereoisomers showed to be viscous oily products which could not be purified by column chromatography and were used directly in the following steps.

Pyrolysis of the mixture of **7c** and its *trans*-stereoisomer gave a mixture of **8c** and **9c**[13] in a ratio of ca. 2.8:1, in which the desired alkene **8c** was somewhat more abundant than **8b** in the above mixture of **8b** and **9b**. Epoxidation of this mixture, followed by silica gel column chromatography of the thus formed mixture of epoxides **2c**, **10c** and **11c** allowed the isolation of epoxide **2c** in 37% overall yield from **3**.

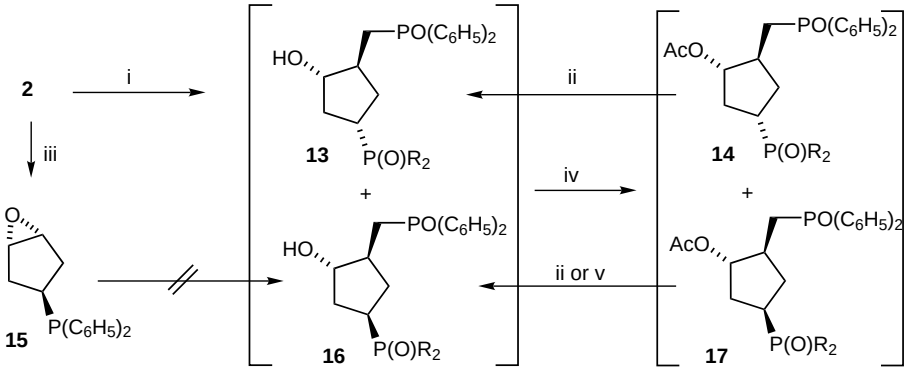
Since we could not obtain an adequate single crystal of any of the epoxides **2** to perform an X-ray diffraction analysis, the relative configuration of **2b** was proposed on the basis of their ^1H and ^{13}C NMR data, including NOESY experiments. The absence of NOE enhancement between 1-H and the 3(4)-H protons is indicative of the *trans*-configuration of **2b**: 1-H and 3(4)-H showed NOE with both 2-H_α and 2-H_β. The observed coupling constant values between atoms (^1H, ^{31}P and ^{13}C) separated by three σ bonds, according to the Karplus relationships, suggest the preferred conformation of **2b** in $CDCl_3$ solution to have an envelope cyclopentane ring in which C1 is out of the plane determined by the rest of cyclopentane carbon atoms on the same side of the epoxide oxygen atom, in such a way that the C(1)-substituent occupies a *pseudoequatorial* arrangement (Fig. 3). Molecular mechanics calculations also suggests this conformation to be the more stable one.[15] Reasonably, the relative configuration of epoxides **2a** and **2c** must be the same, although in the case of **2a**, overlapping of the ^1H NMR signals precluded NOESY experiments and the determination of several coupling constant values.

Next, anhydrous epoxide **2a** (azeotropic distillation of its water content with toluene) was reacted with the lithium derivative of methyldiphenylphosphine oxide in anhydrous THF (Scheme 3). Contrary to our expectations a mixture of stereoisomeric alcohols **13a** and **16a** in a ratio of about 3:1 (^1H NMR, HPLC) was obtained in 62.5% yield. In other runs, the ratio of **13a**/**16a** was around 2:1. Since this mixture could not be separated by silica gel column chromatography or by crystallization, it was transformed into a mixture of the corre-



$^3J(C3/^{31}P) = 12.7$ Hz
$^3J(2\text{-H}\alpha/^{31}P) = 14.5$ Hz
$^3J(2\text{-H}\beta/^{31}P) = 1.0$ Hz
$^3J(2\text{-H}\alpha/2\text{-H}\beta) = 14.5$ Hz
$^3J(1\text{-H}/2\text{-H}\beta) = 8.0$ Hz
$^3J(1\text{-H}/2\text{-H}\alpha) = 10.0$ Hz

Figure 3. Configuration, preferred conformation and several coupling constant values of epoxide **2b**.



13a, **14a**, **16a**, **17a**, R = isoPr; **13b**,**14b**, **16b**, **17b**, R = C_6H_5; **13c**,**14c**, **16c**, **17c**, R = cyclopentyl

Scheme 3. Synthesis of *cis*-1,3-disubstituted cyclopentane 1,4-diphosphines dioxides. *Reagents and conditions*: (i) methyldiphenylphosphine oxide, THF, 1.6 M *n*-BuLi (in hexanes), −78°C; then **2**, rt for 3 h and reflux for 15 h; (ii) NaMeO, MeOH, reflux, 2 h; (iii) $(EtO)_3SiH$, $Ti(OisoPr)_4$, THF, reflux, 7 h; (iv) Ac_2O, reflux, 2 h; (v) KCN, EtOH, reflux, 12 h.

sponding acetates **14a** and **17a** on reaction with acetic anhydride. The mixture of acetates **14a** and **17a** could be separated by flash silica gel column chromatography, thus obtaining pure samples of both compounds, which were fully characterized. The complexity of the ^{1}H NMR spectra of these compounds did not allow us to establish their relative configurations. Fortunately, we could obtain a single crystal of acetate **17a** whose X-ray diffraction analysis was conclusive to establish the *cis*-configuration of the phosphinoyl substituents (Fig. 4). Reaction of these acetates with methanol catalyzed by sodium methoxide gave the corresponding alcohols **13a** and **16a**, which were fully characterized.

In a similar way, starting from **2b**, a mixture of alcohols **13b** and **16b** in an approximate ratio of 3:2 (^{1}H NMR) was obtained, which could not be separated by column chromatography or crystallization. However, as before, we were able to separate the corresponding mixture of acetates **14b** and **17b**, which were obtained in pure form. Reaction of acetates **14b** and **17b** with sodium methoxide in methanol gave the corresponding alcohols **13b** and **16b**. X-Ray diffraction analysis of a single crystal of **13b** allowed us to clearly establish the relative *trans*-configuration of its phosphinoyl substituents (Fig. 5).

A mixture of alcohols **13c** and **16c** (approximate ratio 2.5:1) was also obtained from epoxide **2c**. Separation of the mixture was carried out via the corresponding acetates **14c** and **17c**, whose methanolysis gave back the corresponding alcohols. Worthy of note, methanolysis of acetate **17c** with sodium methoxide in methanol took place with partial epimerization to **13c**. However,

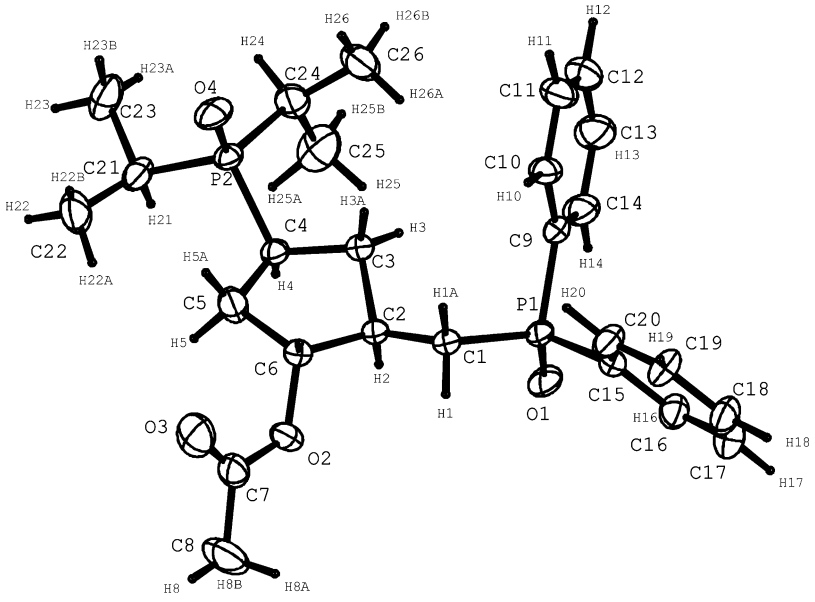


Figure 4. X-Ray diffraction structure (ORTEP) of **17a**.

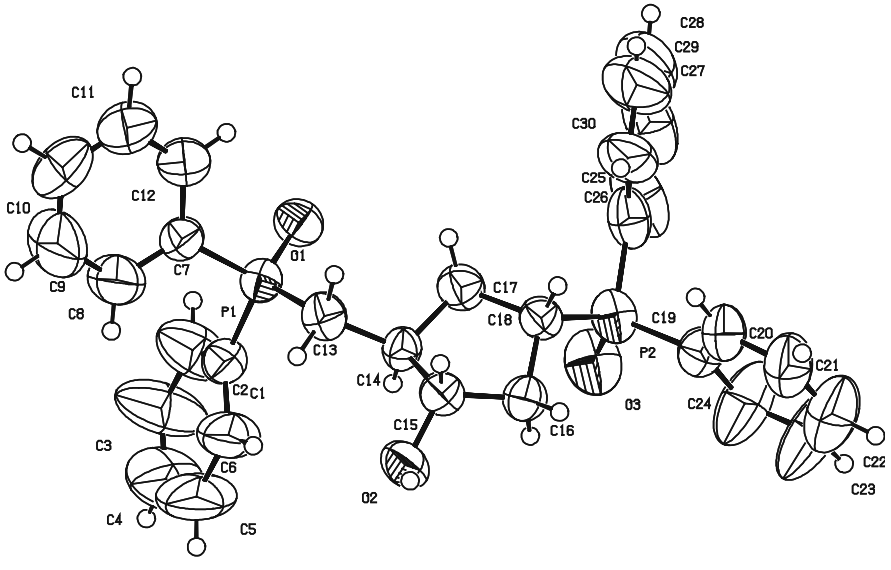
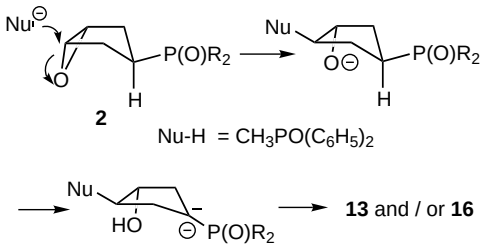


Figure 5. X-Ray diffraction structure (ORTEP) of **13b**.

methanolysis of **17c** to **16c** could be cleanly carried out on reaction with potassium cyanide in ethanol (83% yield).[16]

Comparison of the ^{1}H and ^{13}C NMR data for alcohols **13a–c** and **16a–c** allowed us to clearly establish that in all cases the opening of epoxides **2a–c** gave the unexpected alcohols **13a–c** as the main products, the expected stereoisomers **16a–c** always being the minor components. As expected for the epoxide opening in all of the alcohols **13a–c** and **16a–c**, the hydroxyl and the diphenylphosphinoylmethyl substituents are in a *trans*-arrangement. Since epoxides **2a–c** correspond to only one stereoisomer, an explanation of the experimental results could be related to the acidity of the α-phosphinoyl protons of **2**, which would allow epimerization at C(4) (the carbon atom bearing the dialkyl- or diarylphosphinoyl substituent) in the opened product.

Taking into account the assigned configuration and the preferred conformation of epoxides **2**, the alkoxide initially formed by nucleophilic addition to the epoxide ring of **2** could abstract the close acidic hydrogen atom (4-H) to give an α-phosphinoyl anion whose protonation can take place in two ways to give alcohols **16** or their epimers **13** (Scheme 4).

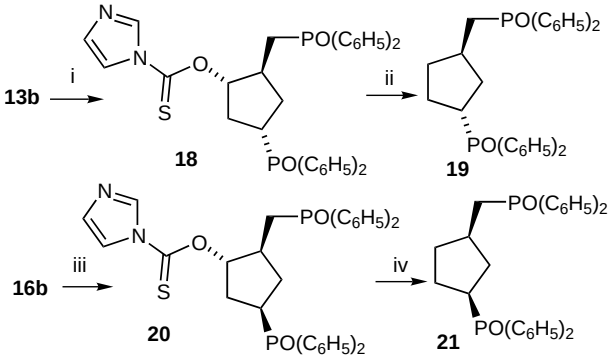


Scheme 4. Possible mechanism for the formation of alcohols **13** and **16** from epoxides **2**.

The preferential formation of the *trans*-derivatives **13** could be indicative of their greater stability. In fact, as stated before, partial epimerization of C(4) was observed during the methanolysis of acetate **17c** using sodium methoxide in methanol.

Since the desired diphosphines should contain both phosphino substituents in a *cis*-arrangement, only the minor products from these reactions are of interest. To solve the problem of the epimerization in the above reaction we carried out the reaction of **2b** with the lithium derivative of methyldiphenylphosphine oxide in THF in the presence of an excess of trimethylsilyl chloride (TMSCl) with the aim of trapping the initially formed alkoxide.[17] However, the only observed product seemed to be the corresponding chlorohydrin, probably formed during the aqueous work up by reaction of **2** with the HCl formed by hydrolysis of the TMSCl. Alternatively, epoxide **2b** was reduced with triethoxysilane[18] catalyzed by titanium tetraisopropoxide to give in good yield (80%) the corresponding phosphine **15** (Scheme 3). Attempted reduction of **2b** with trichlorosilane[3,19] led mainly to the corresponding chlorohydrin, phosphine **15** being not observed. Contrary to expectations, all attempts to open the epoxide function of **15** by reaction with the lithium derivative of methyldiphenylphosphine oxide [(a) in the standard way used for epoxides **2**, (b) in the presence of BF_3 etherate[20] to activate the epoxide, (c) in the presence of tetramethylethylenediamine to increase the reactivity of the lithium derivative, or (d) in the presence of $CeCl_3$, to activate the epoxide and to increase the nucleophilic reactivity of the organometallic reagent[21]] were fruitless. In all cases, most of the starting phosphine was recovered unchanged.

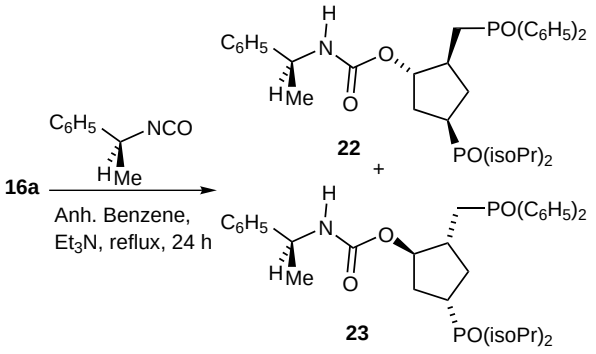
Alcohols **13b** and **16b** were dehydroxylated to compounds **19** and **21**, respectively, through the Barton procedure via the corresponding imidazolylthiocarbonyl derivatives **18** and **20**, respectively,[22] which were reduced with tri-*n*-butyltin hydride[23] (Scheme 5).



Scheme 5. Dehydroxylation of diphosphine dioxides **13b** and **16b**. *Reagents and conditions*: (i) thiocarbonydiimidazole, toluene, reflux, 1 h; (ii) $(n\text{-}Bu)_3SnH$, AIBN, toluene, reflux, 4 h; (iii) thiocarbonydiimidazole, CH_2Cl_2, reflux, 4 h; (iv) $(n\text{-}Bu)_3SnH$, AIBN, benzene, reflux, 6 h.

Although the relative configuration of compounds **19** and **21** should be the same as their precursors **13b** and **16b**, respectively, we were able to carry out an X-ray diffraction analysis of a single crystal of **21**, which confirmed its *cis*-configuration.

To prepare non-racemic precursors of the *cis*-1,3-disubstituted cyclopentane-1,4-diphosphines, racemic alcohol **16a** was reacted with excess (*S*)-α-phenylethylisocyanate (Scheme 6) to give a diastereomeric mixture of the corresponding carbamates, **22** and **23**. The product was separated from *N*,*N*′-bis-(1-phenylethyl)urea by flash column chromatography (silica gel, ethyl acetate/methanol mixtures), and then submitted to a series of crystallizations from ethyl acetate/methanol mixtures. In this way, pure samples of both diastereomers (**22** and **23**) could be obtained in enough quantity to fully characterize them.



Scheme 6. Preparation of carbamates **22** and **23**.

Although, only very minor differences were observed in the IR, NMR (^{1}H, ^{13}C and ^{31}P) and MS spectra of compounds **22** and **23**, both diastereomers are clearly distinguishable by chiral HPLC using a Chiralcel OD-H column containing the chiral stationary phase cellulose tris(3,5-dimethylphenylcarbamate) and show very different optical rotations. The relative configuration of **23** could be obtained by X-ray diffraction analysis (Fig. 6). Knowing, the absolute (*S*)-configuration of the starting α-phenylethylisocyanate, the absolute configuration of **23** should be (α*S*,1*R*,2*R*,4*S*) while that of **22** should be (α*S*,1*S*,2*S*,4*R*).

All of the new compounds described herein have been fully characterized by spectroscopic techniques (IR, ^{1}H, ^{13}C and ^{31}P NMR and MS) and elemental analysis (except phosphine **15**). Assignment of the NMR spectra have been carried out with the aid of COSY ^{1}H/^{1}H, HETCOR ^{1}H/^{13}C, NOESY and DEPT experiments. The relative configurations of alcohols **13** and **16** and acetates **14** and **17** were assigned by comparison of their NMR data with those of alcohol **13b** and acetate **17a**, whose relative configurations were established by X-ray diffraction analysis.

The NMR data for acetates **17** in $CDCl_3$ solution are in accord for a preferred conformation similar to that observed in the solid state for **17a** (Fig. 3). This conformation corresponds to an envelop in which the C(1), C(2), C(4) and C(5) carbon atoms are essentially coplanar (dihedral angle C(4)–C(5)–C(1)–C(2) = −3.90°), with the C(3) atom out of this plane in such a way that the phosphinoyl substituents are in *pseudoequatorial* arrangements. One of the protons of the exocyclic methylene group (H_{anti}) is nearly *antiperiplanar* to 2-H (dihedral angle 2-H–C(2)–C–H_{anti} = 177.1°), while the phosphinoyl substituent connected to this methylene group is *anti* to C(1) and the other hydrogen atom (H_{syn}) is *anti* to C(3). Table 1 collects significant ^3J(^{13}C–^{31}P) for compounds **17a**–**c** and dihedral angles for **17a**, from the X-ray diffraction analysis. Also, the observed ^3J(^{13}C–^{31}P) values are in accord with the assumed conformation (see Table 1), taking into account a Karplus relationship.[24]

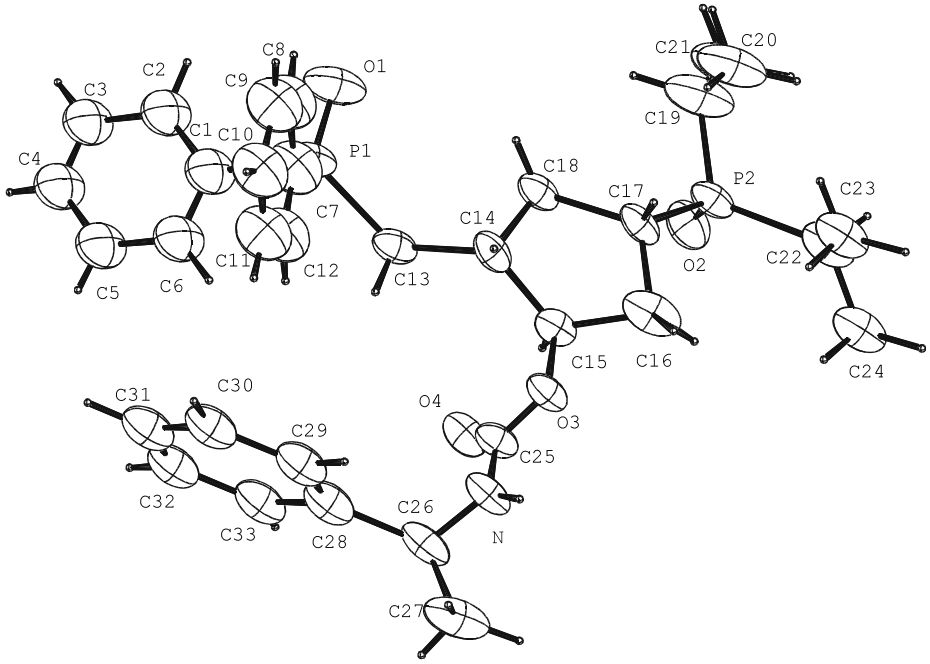


Figure 6. X-Ray diffraction structure of **23**.

Table 1. Significant ^3J(^{13}C–^{31}P) values (Hz) for acetates **17a**–**c** and corresponding alcohols **16a**–**c** and dihedral angles (°) from the single-crystal X-ray diffraction structure of **17a**

^3J(^{13}C–^{31}P) (dihedral angle)	**17a**	**17b**	**17c**	**16a**	**16b**	**16c**
*C*1–*P*O(C_6H_5)$_2$ (C1–C2–CH_2–P)	14.6 (170.2)	14.2	14.8	2.9	1.9	3.3
*C*1–C4–*P*OR_2 (C1–C5–C4–P)	8.5 (146.6)	8.7	9.3	7.5	6.3	7.7
*C*2–C4–*P*OR_2 (C2–C3–C4–P)	8.9 (164.4)	8.6	8.6	9.6	10.2	10.4
*C*3–*P*O(C_6H_5)$_2$ (C3–C2–CH_2–P)	2.4 (−71.7)	≈0	≈0	14.4	14.6	13.7

In the case of alcohols **16**, a conformation of the cyclopentane ring similar to that of acetates was assumed, but the CH_2–$PO(C_6H_5)_2$ bond is rotated by ca. 120° in order to establish an intramolecular hydrogen bond between the phosphinoyl and hydroxyl groups, as previously observed in closely related compounds.[13] In doing so, the H_{syn} proton of an acetate **17** becomes the H_{anti} proton in the corresponding alcohol **16**, and vice versa. This conformation is supported by the significant reduction of the $^3J(^{13}C–^{31}P)$ value between C(1) and the phosphor atom of the CH_2PO group and the significant increase of the $^3J(^{13}C–^{31}P)$ value for C(3) in these alcohols (see Table 1).

However, it is difficult to propose a preferred conformation from the NMR data for alcohols **13**, acetates **14** and compounds **19**, **21**, **22** and **23**.

Preliminary studies have shown that trichlorosilane reduction of the phosphine oxide groups of (±)-**16a** takes place without epimerization at any stereogenic center and that reduction of enantioenriched **23** with trichlorosilane takes place with simultaneous carbamate deprotection,[19] which opens the way to enantioenriched *cis*-1,3-disubstituted cyclopentane-1,4-diphosphines. Work is in progress to develop improved methods to prepare this class of compounds and to study the catalytic activity of the corresponding diphosphines.

3. Conclusions

In conclusion, we have developed a synthetic route to prepare advanced precursors of chiral non-racemic *cis*-1,3-disubstituted cyclopentane-1,4-diphosphines which are of potential interest as ligands for asymmetric catalysts. In spite of the lack of stereoselectivity in the reaction of epoxides **2** with the lithium derivative of methyldiphenylphosphine oxide, the diastereomeric mixtures can be separated via the corresponding acetates, while the enantiomeric mixtures of alcohols **16** can be separated by crystallization of the diastereomeric mixtures of the corresponding carbamates derived from (*S*)-α-phenylethylamine. The relative configuration of representative compounds of this series has been ascertained by X-ray diffraction analysis.

4. Experimental

4.1. General methods

Melting points were determined with a MFB 595010 M Gallenkamp melting point apparatus. Unless otherwise stated, NMR spectra were recorded in $CDCl_3$ in the following spectrometers: ^1H NMR (500 MHz, Varian VXR 500), ^{13}C NMR (75.4 MHz, Varian Gemini 300), ^{31}P NMR (121.4 MHz, Varian Unity 300 Plus). ^1H and ^{13}C NMR chemical shifts (δ) are reported in ppm with respect to internal tetramethylsilane (TMS) and ^{31}P NMR chemical shifts (δ) are reported in ppm relative to 85% H_3PO_4 as external standard. The multiplicity of the signals is: s, singlet; d, doublet; t, triplet; q, quartet; quint, quintuplet; h, heptuplet. For the different cyclopentanes, the terms H_α or H_β are assigned to hydrogen atoms which are *cis* or *trans* relative to the reference substituent (usually at position 1), respectively. IR spectra were recorded on a FT/IR Perkin–Elmer spectrometer, model 1600; only significant absorption bands are given. Routine MS spectra were taken on a Hewlett–Packard 5988A spectrometer, the sample was introduced directly or through a gas chromatograph, Hewlett–Packard model 5890 Series II, equipped with a 30 m HP-5 (5% diphenyl–95% dimethylpolysiloxane) column [conditions A: 10 psi, initial temperature: 100°C (2 min), then heating at a rate of 15°C/min until 250°C, then isothermal; conditions B: 10 psi, initial temperature: 200°C (2 min), then heating at a rate of 15°C/min until 300°C, then isothermal; conditions C: 10 psi, initial temperature: 100°C (2 min), then heating at a rate of 8°C/min until 250°C, then isothermal] and the electron impact technique (70 eV). Only significant ions are given: those with higher relative abundance, except for the ions with higher m/z values. Silica gel SDS 60 (70–200 μm) or (35–70 μm) was utilized for the standard and flash column chromatography, respectively. Optical rotations were measured on a Perkin–Elmer, model 241 polarimeter. Chiral HPLC analyses were performed on a Waters model 600 liquid chromatograph provided with variable λ detector, working at $\lambda = 220$ nm and using a Chiralcel OD-H column (25×0.46 cm) containing the chiral stationary phase cellulose tris-(3,5-dimethylphenylcarbamate), conditions A: hexane/isopropanol in the ratio of 90:10 as eluent, flow 0.5 mL/min. Chlorodiisopropylphosphine and chlorodiphenylphosphine were purchased from Aldrich Chemical Co. and chlorodicyclopentylphosphine was prepared according to the method previously described.[14] NMR and routine MS spectra were performed at the *Serveis Científico-Tècnics* of the University of Barcelona, while elemental analyses were carried out at the Microanalysis Service of the *Centro de Investigación y Desarrollo* (C.I.D.), C.S.I.C., Barcelona, Spain.

4.1.1. *trans*-(3,4-Epoxycyclopentyl)diisopropylphosphine oxide 2a

4.1.1.1. 3-Cyclopentenol.[11] To a solution of freshly distilled cyclopentadiene (30 g, 455 mmol) in anhydrous THF (100 mL) was added dropwise a solution of BH_3·THF (100 mL, 1 M in THF, 100 mmol) keeping the temperature below 25°C. When the addition was complete, the solution was stirred at room temperature for 2 h. The mixture was concentrated under reduced pressure and the residue was treated with 3N NaOH (40 mL), diethyl ether (100 mL). Then, aqueous solution of H_2O_2 (40 mL, 30%) was added dropwise and when the addition was over, the mixture was stirred for 30 min. The organic phase was separated and the aqueous one was extracted with diethyl ether (2×40 mL). The combined organic phase and extracts were dried (Na_2SO_4), filtered and concentrated under moderate vacuum to give impure 3-cyclopentenol as a yellow oil (7.69 g, 31% approx. yield), which was kept at −30°C, and was used as such in the next step. The ^1H and ^{13}C NMR spectra of this product suggested the presence of cyclopentanol and *n*-butanol.

4.1.1.2. 3-Cyclopentenyl bromide. To a solution of 3-cyclopentenol (7.00 g, 83 mmol approx.) in pentane (27 mL) at −20°C was added a solution of PBr_3 (3.2 mL, 33.2 mmol) in pentane (5 mL) and the mixture was heated under reflux for 12 h. The mixture was allowed to cool to room temperature, cold (0°C) H_2O (50 mL) was added and the organic phase was separated. The aqueous phase was extracted with pentane (3×30 mL) and the combined organic extracts were dried (Na_2SO_4), filtered and concentrated under moderate vacuum to give impure 3-cyclopentenyl bromide as an oil (8.5 g, 70% approx. yield, containing bromocyclopentane and 1-bromobutane (^1H and ^{13}C NMR).

4.1.1.3. (3-Cyclopentenyl)diisopropylphosphine oxide. To a suspension of dried Mg (662 mg, 27.2 mmol) in anhydrous THF (5 mL), a crystal of I_2 was added and the mixture was stirred for 10 min. Then, a solution of 3-cyclopentenyl bromide (4.0 g, 27.2 mmol approx.) in anhydrous THF (10 mL) was added dropwise and the mixture was stirred at room temperature for 5 h. This solution was added through a transfer to a cold (ice-bath) solution of chlorodiisopropylphosphine (1.7 mL, 1.57 g, 96% content, 10.3 mmol) in anhydrous THF (8 mL) and the mixture was stirred for 18 h, while it was allowed to slowly reach room temperature. Aqueous saturated solution of NH_4Cl (20 mL) and 2N H_2SO_4 (6 mL) were added and the mixture was concentrated in vacuo to dryness. The yellow residue was washed with hot diethyl ether (200 mL) for 1 h. The solution was discarded and the residue was dissolved in H_2O (50 mL), was made basic with 5N NaOH (16 mL), and extracted with ethyl acetate (9×100 mL). The combined organic extracts were dried (Na_2SO_4), filtered and concentrated under vacuum to give a dark oil (1.75 g), which was submitted to flash column chromatography [silica gel (70 g), ethyl acetate/methanol mixtures]. On elution with a mixture of ethyl acetate/methanol in the ratio of 96.5:3.5, a mixture of products was obtained. GC/MS (conditions C) showed it to contain: *n*-butyldiisopropylphosphine oxide (t_r = 9.3 min), (3-cyclopentenyl)diisopropylphosphine oxide (t_r = 11.9 min) and cyclopentyldiisopropylphosphine oxide (t_r = 12.0 min), whose relative areas were 26:59:12. This mixture could not be separated by distillation (50°C/0.5 Torr) or by neutral aluminum oxide column chromatography and was used as such in the next step. Compound of t_r = 11.9 min: GC/MS (EI), *m*/*z* (%): 200 ($M^{\bullet+}$, 4), 157 [$(M-C_3H_7)^+$, 4], 134 [$(M-C_5H_6)^{\bullet+}$, 69], 92 [$(M-C_3H_6-C_5H_6)^{\bullet+}$, 100].

4.1.1.4. Epoxide 2a. To a solution of (3-cyclopentenyl)diisopropylphosphine oxide (from a different run to that described under 4.1.1.3.) (1.53 g, 47% relative area by GC/MS, 3.6 mmol approx.) in CH_2Cl_2 (30 mL), *m*-CPBA (4.63 g, 57% content, 15.3 mmol) was added and the mixture was stirred at room temperature for 18 h. More CH_2Cl_2 (20 mL) was added and the solution was washed with 5N NaOH (15 mL) and brine (30 mL). The organic phase was dried (Na_2SO_4), filtered and evaporated under reduced pressure to give a yellow residue (1.21 g). Flash column chromatography [silica gel (75 g), ethyl acetate/methanol] gave **2a** as an oil (220 mg, 28% approx. yield). IR (KBr) 1172, 1147 (P=O st) cm^{-1}; ^1H NMR 3.52 [s, 2H, 3(4)-H], 2.18–1.97 [complex signal, 7H, 1-H, 2(5)-H_α, 2(5)-H_β [δ 2.02, dh, J = 12.5 Hz, J' = 7.0 Hz, 2H, 2 C<u>H</u>$(CH_3)_2$]], 1.18 (dd, J = 7.5 Hz, J' = 14.5 Hz, 6H) and 1.16 (dd, J = 7.0 Hz, J' = 14.5 Hz, 6H) [2 CH(C<u>H</u>$_3)_2$]; ^{13}C NMR 56.6 [CH, d, $^3J_{C-P}$ = 11.1 Hz, C3(4)], 28.3 [CH_2, s, C2(5)], 27.0 (CH, d, $^1J_{C-P}$ = 63.1 Hz, C1), 26.4 [CH, d, $^1J_{C-P}$ = 63.2 Hz, <u>C</u>H$(CH_3)_2$], 16.8 (CH_3, broad s) and 16.5 (CH_3, broad s) [2 CH(<u>C</u>H$_3)_2$]; ^{31}P NMR 53.7; GC/MS (EI) (conditions *C*, t_r = 6.88 min), *m*/*z* (%): 217 [$(M+H)^+$, 4], 216 ($M^{\bullet+}$, 2), 215 [$(M-H)^+$, 7], 174 [$(M-C_3H_6)^{\bullet+}$, 85], 146 [$(M-C_3H_6-CO)^{\bullet+}$, 70], 134 [$(M-C_5H_6O)^{\bullet+}$, 79], 131 [$(M-C_3H_6-C_3H_7)^+$, 34], 113 (73), 92 [$(M-C_5H_6O-C_3H_6)^{\bullet+}$, 74], 83 [$(C_5H_7O)^+$, 51], 67 ($C_5H_7^+$, 100). Anal. calcd for $C_{11}H_{21}O_2P{\cdot}0.5H_2O$: C, 58.65; H, 9.85. Found: C, 58.53; H, 9.83%.

4.1.2. 3-(Diphenylphosphinoyl)cyclopentanone 4b. A mixture of 2-cyclopentenone (1.00 g, 1.02 mL, 12.2 mmol), acetic acid (99.7%, 1.00 mL, 17.4 mmol) and molecular sieves (4 Å, 200 mg) was stirred at room temperature for 1 h. The mixture was cooled (ice-bath) and chlorodiphenylphosphine (95%, 2.25 mL, 11.9 mmol) was added dropwise. When the addition was over, the ice-bath was removed and the mixture was stirred at room temperature for 2 h. The solution was poured into H_2O (10 mL) and the mixture was extracted with $CHCl_3$ (4×7 mL). The combined organic phases were washed with $NaHCO_3$ (saturated aqueous solution, 4×4 mL), dried (Na_2SO_4) filtered and evaporated under reduced pressure to give pure **4b** as a yellow viscous oil (3.35 g, 99% yield). IR (NaCl) 1738 (C=O st), 1184, 1119 (P=O st) cm^{-1}; ^1H NMR 7.80–7.70 (complex signal, 4H, Ar-H_{ortho}), 7.54–7.42 (complex signal, 6H, Ar-H_{para}, Ar-H_{meta}), 3.07–2.98 (m, 1H, 3-H), 2.58 (dddd, J = 1.0 Hz, J' = 11.0 Hz, J'' = 16.0 Hz, J''' = 18.5 Hz, 1H, 2-H_α), 2.45–2.36 (m, 1H, 5-H_α), 2.32–2.21 (complex signal, 2H, 2-H_β, 4-H_β), 2.18 (dd, J = 8.5 Hz, J' = 18.0 Hz, 5-H_β), 1.98 (m, 1H, 4-H_α); ^{13}C NMR 215.8 (C, d, $^3J_{C-P}$ = 12.6 Hz, C1), 131.9 (CH, d, $^4J_{C-P}$ = 2.7 Hz, Ar-CH_{para}), 131.7 (C, d, $^1J_{C-P}$ = 98.2 Hz) and 131.1 (C, d, $^1J_{C-P}$ = 98.2 Hz) (Ar-C_{ipso}), 130.8 (CH, d, $^2J_{C-P}$ = 9.3 Hz) and 130.6 (CH, d, $^2J_{C-P}$ = 8.8 Hz) (Ar-CH_{ortho}), 128.7 (CH, d, $^3J_{C-P}$ = 11.5 Hz, Ar-CH_{meta}), 38.0 (CH_2, d, $^3J_{C-P}$ = 6.0 Hz, C5), 37.9 (CH_2, d, $^2J_{C-P}$ = 2.2 Hz, C2), 35.2 (CH, d, $^1J_{C-P}$ = 76.8 Hz, C3), 22.5 (CH_2, d, $^2J_{C-P}$ = 2.2 Hz, C4); ^{31}P NMR 30.0; MS (EI), *m*/*z* (%): 285 [$(M+H)^+$, 7], 284 ($M^{\bullet+}$, 17), 283 [$(M-H)^+$, 13], 202 [$[HPO(C_6H_5)_2]^{\bullet+}$, 100], 201 (70). Anal. calcd for $C_{17}H_{17}O_2P{\cdot}0.5H_2O$: C, 69.61; H, 6.19. Found: C, 69.62; H, 6.07%.

4.1.3. 3-(Dicyclopentylphosphinoyl)cyclopentanone 4c. From 2-cyclopentenone (3.04 g, 3.16 mL, 37.0 mmol), acetic acid (5 mL), molecular sieves (4 Å, 200 mg) and chlorodicyclopentylphosphine[14] (7.57 g, 37.1 mmol) and following the procedure described for **4b**, pure **4c** was obtained as a yellow viscous oil (9.90 g, quantitative yield). IR (NaCl) 1740 (C=O st), 1155, 1118 (P=O st) cm^{-1}; ^1H NMR 2.59–2.48 (m, 1H, 2-H_α), 2.48–2.35 (complex signal, 3H, 2-H_β, 3-H, 5-H_α), 2.26–2.00 (complex signal, 5H, cyclopentyl CH, 4-H_α, 4-H_β, 5-H_β),

1.96–1.52 (complex signal, 16H, cyclopentyl CH_2); ^{13}C NMR 216.2 (C, d, $^3J_{CP}=12.7$ Hz, C1), 38.6 (CH_2, s, C2), 37.5 (CH_2, d, $^1J_{CP}=6.0$ Hz, C5), 36.7 (CH, d, $^1J_{CP}=67.0$ Hz) and 36.5 (CH, d, $^1J_{CP}=67.0$ Hz) (cyclopentyl CH), 34.0 (CH, d, $^1J_{CP}=67.0$ Hz, C3), 26.8–26.6 (CH_2, complex signal, cyclopentyl C2 and C5), 26.0–25.7 (CH_2, complex signal, cyclopentyl C3 and C4), 23.3 (CH_2, d, $^2J_{C-P}=2.4$ Hz, C4); ^{31}P NMR 50.2; MS (EI), m/z (%): 268 ($M^{\bullet+}$, 4), 200 [$(M-C_5H_8)^{\bullet+}$, 20], 186 [$[HPO(C_5H_9)_2]^{\bullet+}$, 36], 119 (41), 118 [$[H_2POC_5H_9]^{\bullet+}$, 45], 83 [$[M-PO(C_5H_9)_2]^+$, 100]. Anal. calcd for $C_{15}H_{25}O_2P\cdot0.75H_2O$: C, 63.92; H, 9.48. Found C, 64.03; H, 9.52%.

4.1.4. (3,3-Dimethoxycyclopentyl)diphenylphosphine oxide 5b. To a cold (ice-bath) solution of **4b** (3.07 g, 10.8 mmol) in methanol (35 mL), solid $NaBH_4$ (0.79 g, 20.9 mmol) was added portionwise for 1 h. When the addition was over, the ice-bath was removed and the mixture was stirred at room temperature for 18 h. The solvent was evaporated under reduced pressure, the residue was treated with aqueous 5N NaOH (21 mL) and the mixture was heated under reflux for 30 min. The mixture was allowed to cool to room temperature, 6N HCl (18 mL) was added and the solution was extracted with $CHCl_3$ (6×10 mL). The combined organic phases were dried (Na_2SO_4), filtered and evaporated under reduced pressure to give a brown viscous oil mixture of **5b** and alcohol **6b** (ratio 2.6:1, ^1H NMR) (2.84 g, 59.7% yield of **5b** and 23% yield of **6b**). Standard column chromatography [silica gel (150 g), ethyl acetate] allowed clean separation of the products. An analytical sample of **5b** was obtained as a white solid by crystallization, mp 144–144.5°C (ethyl acetate). IR (KBr) 1181, 1119 (P=O st) cm^{-1}; ^1H NMR 7.77–7.72 (m, 4H, Ar-H_{ortho}), 7.50–7.40 (complex signal, 6H, 4 Ar-H_{meta}, 2 Ar-H_{para}), 3.16 (s, 3H) and 3.14 (s, 3H) (2 OCH_3), 2.94–2.85 (m, 1H, 1-H), 2.10–1.97 (complex signal, 2H, 2-H_β, 5-H_β), 1.97–1.89 (complex signal, 2H, 2-H_α, 4-H_β or 4-H_α), 1.86–1.80 (m, 1H, 4-H_α or 4-H_β), 1.80–1.72 (m, 1H, 5-H_α); ^{13}C NMR 132.8 (C, d, $^1J_{C-P}=96.6$ Hz) and 132.5 (C, d, $^1J_{C-P}=97.1$ Hz) (Ar-C_{ipso}), 131.5 (CH, d, $^4J_{C-P}=1.5$ Hz, Ar-CH_{para}), 130.8 (CH, d, $^2J_{C-P}=8.8$ Hz) and 130.7 (CH, d, $^2J_{C-P}=8.2$ Hz) (Ar-CH_{ortho}), 128.5 (CH, d, $^3J_{C-P}=11.5$ Hz, Ar-CH_{meta}), 111.1 (C, d, $^3J_{C-P}=12.6$ Hz, C3), 50.2 (CH_3, s) and 48.6 (CH_3, s) (2 OCH_3), 35.0 (CH, d, $^1J_{C-P}=76.3$ Hz, C1), 34.0 (CH_2, d, $^2J_{C-P}=1.7$ Hz, C2), 33.5 (CH_2, d, $^3J_{C-P}=6.6$ Hz, C4), 22.9 (CH_2, s, C5); ^{31}P NMR 31.5; MS (EI), m/z (%): 330 ($M^{\bullet+}$, 0,5), 329 [$(M-H)^+$, 0,6], 299 [$(M-CH_3O)^+$, 6], 202 [$[HPO(C_6H_5)_2]^{\bullet+}$, 17], 201 [$[PO(C_6H_5)_2]^+$, 17], 129 [$[M-PO(C_6H_5)_2]^+$, 56], 97 [$[M-CH_3OH-PO(C_6H_5)_2]^+$, 100]. Anal. calcd for: $C_{19}H_{23}O_3P$: C, 69.07; H, 7.02. Found C, 69.32; H, 7.01%.

4.1.5. *cis*-3-(Diphenylphosphinoyl)cyclopentanol 6b. Methanol (375 mL) was treated with $NaBH_4$ (2.66 g, 70.3 mmol) for 30 min. The mixture was cooled (ice-bath) and was added to solid **4b** (20.0 g, 70.4 mmol). More $NaBH_4$ (5.30 g, 140 mmol) was added portionwise for 1 h. When the addition was over, the ice-bath was removed and the mixture was stirred at room temperature for 18 h. The solvent was evaporated under reduced pressure, the residue was treated with aqueous 5N NaOH (220 mL) and the mixture was heated under reflux for 30 min. The mixture was allowed to cool to room temperature, 6N HCl (300 mL) was added until neutral pH and the solution was extracted with $CHCl_3$ (3×245 mL). The combined organic phases were dried (Na_2SO_4), filtered and evaporated under reduced pressure to give a mixture of **6b** and its *trans*-stereoisomer in the ratio of 6:1 (^1H NMR) as a pale brown solid (19.4 g, 96%). An analytical sample of **6b** was obtained by crystallization, mp 145–146°C (ethyl acetate). IR (KBr) 3321 (OH st), 1152, 1120 (P=O st) cm^{-1}; ^1H NMR 7.80–7.73 (complex signal, 4H, Ar-H_{ortho}), 7.53–7.42 (complex signal, 6H, Ar-H_{meta}, Ar-H_{para}), 5.20–4.80 (broad s, 1H, OH), 4.28 (broad s, 1H, 1-H), 3.02–2.94 (m, 1H, 3-H), 2.14–1.96 (complex signal, 3H, 2-H_α, 2-H_β, 4-H_β or 4-H_α), 1.94–1.82 (complex signal, 2H, 4-H_α or 4-H_β, 5-H_α), 1.77–1.68 (m, 1H, 5-H_β); ^{13}C NMR 132.9 (C, higher δ signal of a d) and 131.5 (C, d, $^1J_{C-P}=97.7$ Hz) (Ar-C_{ipso}), 131.7 (CH, d, $^4J_{C-P}=2.7$ Hz) and 131.6 (CH, d, $^4J_{C-P}=2.8$ Hz) (Ar-CH_{para}), 130.8 (CH, d, $^2J_{C-P}=8.8$ Hz) and 130.7 (CH, d, $^2J_{C-P}=8.8$ Hz) (Ar-CH_{ortho}), 128.6 (CH, d, $^3J_{C-P}=11.0$ Hz, Ar-CH_{meta}), 72.7 (CH, s, C1), 36.6 (CH_2, d, $^3J_{C-P}=4.5$ Hz, C5), 35.8 (CH_2, d, $^2J_{C-P}=1.7$ Hz, C2), 34.7 (CH, d, $^1J_{C-P}=71.3$ Hz, C3), 23.4 (CH_2, d, $^2J_{C-P}=2.8$ Hz, C4); ^{31}P NMR 39.9; MS (EI), m/z (%): 286 ($M^{\bullet+}$, 2), 285 [$(M-H)^+$, 2], 243 (22), 229 (32), 202 [$[HPO(C_6H_5)_2]^{\bullet+}$, 100], 201 (34). Anal. calcd for $C_{17}H_{19}O_2P\cdot0.25H_2O$: C, 70.21; H, 6.76. Found: C, 70.24; H, 6.68%.

4.1.6. Mixture of *cis*-3-(dicyclopentylphosphinoyl)-cyclopentanol 6c and its *trans*-stereoisomer. From $NaBH_4$ (4.32 g, 114 mmol), methanol (230 mL) and ketone **4c** (10.21 g, 38.1 mmol) and following the procedure described for **6b**, a mixture of **6c** and its *trans*-stereoisomer in the ratio of 9:1 (^1H NMR) was obtained (8.91 g, 87%) as a pale brown oil, which was characterized and used as such in the next step. IR (NaCl) 3377 (OH st), 1144 (P=O st) cm^{-1}; MS (EI), m/z (%): 270 ($M^{\bullet+}$, 2), 202 (41), 201 [$(M-C_5H_9)^+$, 34], 186 [$[HPO(C_5H_9)_2]^{\bullet+}$, 100], 145 [$(M-C_5H_8O-C_3H_5)^+$, 40], 134 [$(M-2\ C_5H_8)^{\bullet+}$, 36]. Anal. calcd for $C_{15}H_{27}PO_2\cdot0.5H_2O$: C, 64.49; H, 10.10. Found: C, 64.69; H, 10.17%. Data for **6c** from the spectra of the mixture: ^1H NMR 4.50–4.30 (broad s, 1H, OH), 4.27 (m, 1H, 1-H), 2.30–2.04 (complex signal, 6H, cyclopentyl CH, 2-H_α, 2-H_β, 3-H, 4-H_α), 2.00–1.55 (complex signal, 19H, cyclopentyl CH_2, 4-H_β, 5-H_α, 5-H_β); ^{13}C NMR 72.4 (CH, d, $^3J_{C-P}=5.5$ Hz, C1), 36.8 (CH, d, $^1J_{C-P}=65.9$ Hz) and 36.6 (CH, d, $^1J_{C-P}=66.4$ Hz) (cyclopentyl C1), 36.2 (CH_2, broad s, C2), 35.9 (CH_2, d, $^3J_{C-P}=6.6$ Hz, C5), 34.3 (CH, d, $^1J_{C-P}=63.7$ Hz, C3), 27.4 (2 CH_2, s), 27.2 (CH_2, s) and 27.1 (CH_2, s) (cyclopentyl C2 and C5), 26.3 (CH_2, d, $^3J_{C-P}=9.9$ Hz) and 26.2 (CH_2, d, $^3J_{C-P}=9.9$ Hz) (cyclopentyl C3 and C4), 26.0 (CH_2, d, $^3J_{C-P}=9.9$ Hz), 25.9 (CH_2, d, $^3J_{C-P}=9.9$ Hz), 24.1 (CH_2, d, $^2J_{C-P}=2.7$ Hz, C4); ^{31}P NMR 56.0. Data for the *trans*-stereoisomer of **6c** from the spectrum of the mixture: ^{31}P NMR 52.5.

4.1.7. *cis*-3-(Diphenylphosphinoyl)cyclopentyl methanesulfonate 7b. To a cold (ice-bath) solution of a mixture of **6b** and its *trans*-stereoisomer (19.4 g, 67.8 mmol) in anhydrous CH_2Cl_2 (345 mL), anhydrous triethylamine (23.7 mL, 17.2 g, 170 mmol) and 4-(dimethylamino)pyridine (830 mg, 6.8 mmol) were added. The solution was stirred for 5 min and methanesulfonyl chloride (6.44 mL, 98% content, 81 mmol) was added dropwise and the mixture was stirred for 6 h. The ice-bath was removed, the mixture was diluted with CH_2Cl_2 (170 mL) and the solution was washed with NH_4Cl (saturated aqueous solution, 2×345 mL) and 2N HCl (2×250 mL). The organic phase was dried (Na_2SO_4), filtered and evaporated in vacuo to give a mixture of **7b** and its *trans*-stereoisomer in the ratio of 6:1 (^{1}H NMR) as a foamy brown solid (21.1 g, 82%). An analytical sample of **7b** was obtained by crystallization, mp 129–130°C (ethyl acetate). IR (KBr) 1346 (SO_2 st), 1180, 1121 (P=O st and SO_2 st) cm^{-1}; ^{1}H NMR 7.77–7.70 (complex signal, 4H, Ar-H$_{ortho}$), 7.53–7.42 (complex signal, 6H, Ar-H$_{meta}$, Ar-H$_{para}$), 5.14 (broad pseudo quint, $J=6.0$ Hz, 1H, 1-H), 2.96 (s, 3H, SO_2CH_3), 2.76 (pseudo dq, $J=9.0$ Hz, $J'=3.5$ Hz, 1H, 3-H), 2.31–2.03 (complex signal, 4H, 2-H$_\alpha$, 2-H$_\beta$, 4-H$_\beta$, 5-H$_\alpha$), 2.03–1.94 (m, 1H, 5-H$_\beta$), 1.86–1.74 (m, 1H, 4-H$_\alpha$); ^{13}C NMR 133.0 (C, higher δ signal of a d) and 132.1 (C, d, $^1J_{C-P}=97.7$ Hz) (Ar-C$_{ipso}$), 131.7 (CH, d, $^4J_{C-P}=2.2$ Hz, Ar-CH$_{para}$), 130.8 (CH, d, $^2J_{C-P}=9.4$ Hz) and 130.7 (CH, d, $^2J_{C-P}=9.3$ Hz) (Ar-CH$_{ortho}$), 128.62 (CH, d, $^3J_{C-P}=11.5$ Hz) and 128.59 (CH, d, $^3J_{C-P}=11.5$ Hz) (Ar-CH$_{meta}$), 81.6 (CH, d, $^3J_{C-P}=11.0$ Hz, C1), 38.7 (CH_3, s, SO_2CH_3), 35.5 (CH, d, $^1J_{C-P}=75.8$ Hz, C3), 33.5 (CH_2, d, $^3J_{C-P}=8.8$ Hz, C5), 32.8 (CH_2, s, C2), 23.5 (CH_2, d, $^2J_{C-P}=1.1$ Hz, C4); ^{31}P NMR 30.7; MS (EI), m/z (%): 269 [(M−SO_3CH_3)$^+$, 24], 268 (17), 203 (24), 202 [[HPO(C_6H_5)$_2$]$^{\bullet+}$, 100], 201 (93). Anal. calcd for: $C_{18}H_{21}O_4PS\cdot0.25H_2O$: C, 58.60; H, 5.88. Found: C, 58.83; H, 5.79%.

4.1.8. Mixture of *cis*-3-(dicyclopentylphosphinoyl)cyclopentyl methanesulfonate 7c and its *trans*-stereoisomer. From a mixture of **6c** and its *trans*-stereoisomer in the ratio of 9:1 (7.93 g, 29.4 mmol), anhydrous CH_2Cl_2 (200 mL), anhydrous triethylamine (10.3 mL, 74 mmol), 4-(dimethylamino)pyridine (359 mg, 2.94 mmol) and methanesulfonyl chloride (2.78 mL, 98% content, 35.2 mmol) and following the procedure described for **6b**, a mixture of **7c** and its *trans*-stereoisomer was obtained as a brown oil (8.94 g, 87%), which was characterized and used as such in the next step. IR (NaCl) 3416 (OH st, H_2O), 1349 (SO_2 st), 1197, 1177 (P=O st and SO_2 st) cm^{-1}; spectroscopic data for **7c**: GC/MS (conditions B, $t_r=7.62$ min), m/z (%): 252 [(M−CH_3SO_3H)$^{\bullet+}$, 9], 186 [[HPO(C_5H_9)$_2$]$^{\bullet+}$, 96], 185 (33), 145 (61), 119 (87), 118 [[H_2PO(C_5H_9)]$^{\bullet+}$, 100]; ^{1}H NMR 5.17 (m, 1H, 1-H), 3.04 (s, 3H, CH_3SO_3), 2.45–2.35 (m, 1H, 3-H), 2.30–2.00 (complex signal, 6H, cyclopentyl CH, 2-H$_\beta$ or 2-H$_\alpha$, 4-H$_\beta$, 5-H$_\alpha$, 5-H$_\beta$), 2.00–1.50 (complex signal, 18H, cyclopentyl CH_2, 2-H$_\alpha$ or 2-H$_\beta$, 4-H$_\alpha$); ^{13}C NMR 82.1 (CH, d, $^3J_{C-P}=10.5$ Hz, C1), 38.4 (CH_3, s, CH_3SO_3), 36.8 (CH, d, $^1J_{C-P}=66.9$ Hz) and 36.7 (CH, d, $^1J_{C-P}=66.4$ Hz) (cyclopentyl CH), 35.1 (CH, d, $^1J_{C-P}=65.3$ Hz, C3), 33.8 (CH_2, s, C2), 33.4 (CH_2, d, $^3J_{C-P}=9.3$ Hz, C5), 27.0–26.9 (CH_2, complex signal, cyclopentyl C2 and C5), 26.1–25.9 (CH_2, complex signal, cyclopentyl C3 and C4), 24.5 (CH_2, d, $^2J_{C-P}=1.1$ Hz, C4); ^{31}P NMR 54.2.

4.1.9. Mixture of (2-cyclopentenyl)diphenylphosphine oxide 9b and (3-cyclopentenyl)diphenylphosphine oxide 8b. The above mixture of **7b** and its *trans*-stereoisomer (21.1 g, 55.5 mmol) was heated in vacuo (135°C/1.0 Torr) for 6 h. The dark brown oil product formed was dissolved in CH_2Cl_2 (200 mL) and the solution was washed with aqueous 2N NaOH (2×175 mL), dried (Na_2SO_4), filtered and evaporated to dryness to give a solid mixture of **9b**,[13] and **8b** (14.6 g, 98% yield) in the approximate relative ratio of 1:1.8 by ^{1}H NMR. An analytical sample of **8b** was obtained as a solid by standard column chromatography [silica gel (70 g), ethyl acetate] followed by crystallization, mp 151.5–152.5°C (ethyl acetate). IR (KBr) 1185, 1118 (P=O st) cm^{-1}; ^{1}H NMR 7.78–7.73 (m, 4H, Ar-H$_{ortho}$), 7.51–7.46 (m, 2H, Ar-H$_{para}$), 7.46–7.41 (m, 4H, Ar-H$_{meta}$), 5.66 [broad s, 2H, 3(4)-H], 3.12 (dtt, $J=4.5$ Hz, $J'=8.5$ Hz, $J''=10.0$ Hz, 1H, 1-H), 2.83–2.71 [m, 2H, 2(5)-H$_\alpha$], 2.57–2.47 [m, 2H, 2(5)-H$_\beta$]; ^{13}C NMR 133.0 (C, d, $^1J_{C-P}=96.7$ Hz, Ar-C$_{ipso}$), 131.4 (CH, d, $^4J_{C-P}=2.8$ Hz, Ar-CH$_{para}$), 130.9 (CH, d, $^2J_{C-P}=8.8$ Hz, Ar-CH$_{ortho}$), 129.3 [CH, d, $^3J_{C-P}=7.9$ Hz, C3(4)], 128.4 (CH, d, $^3J_{C-P}=11.3$ Hz, Ar-CH$_{meta}$), 35.0 (CH, d, $^1J_{C-P}=75.3$ Hz, C1), 33.2 [CH_2, C2(5)]; ^{31}P NMR 32.8; MS (EI), m/z (%): 268 (M$^{\bullet+}$, 5), 202 [[HPO(C_6H_5)$_2$]$^{\bullet+}$, 100], 201 (28), 155 (34). Anal. calcd for: $C_{17}H_{17}OP$: C, 76.10; H, 6.39. Found: C, 75.97; H, 6.56%.

4.1.10. Mixture of (2-cyclopentenyl)dicyclopentylphosphine oxide 9c and (3-cyclopentenyl)dicyclopentylphosphine oxide 8c. Heating a mixture of **7c** and its *trans*-stereoisomer (38.0 g, 0.11 mol) at 120°C/0.5 Torr for 12 h, and following the work-up procedure described for **7b**, a mixture of **9c** and **8c** in a ratio of 1:2.8 (^{1}H NMR) was obtained (26.4 g, 96%). The two compounds could not be separated by column chromatography and were characterized as a mixture. An oily analytical sample of the mixture was obtained by distillation (100°C/0.5 Torr). IR (NaCl) 1158 (P=O st) cm^{-1}; MS (EI), m/z (%): 252 (M$^{\bullet+}$, 2), 186 [[(HPO(C_5H_9)$_2$]$^{\bullet+}$, 51], 145 (48), 119 (75), 118 [[(H_2POC$_5$H$_9$)$^{\bullet+}$, 84], 69 ($C_5H_9^+$, 41), 67 ($C_5H_7^+$, 100). Data for **8c** from the spectra of the mixture: ^{1}H NMR 5.70 (broad s, 2H, 3(4)-H), 2.74–2.54 (complex signal, 5H, 1-H, 2(5)-H$_\alpha$, 2(5)-H$_\beta$), 2.20–1.95 (complex signal, cyclopentyl CH), 1.94–1.48 (complex signal, 16H, cyclopentyl CH_2); ^{13}C NMR 129.3 [CH, d, $^3J_{C-P}=6.6$ Hz, C3(4)], 36.7 [CH, d, $^1J_{C-P}=66.3$ Hz, cyclopentyl CH], 34.2 (CH, d, $^1J_{C-P}=65.3$ Hz, C1), 33.7 [CH_2, s, C2(5)], 26.9 (CH_2, s, cyclopentyl C2 and C5), 25.99 (CH_2, d, $^3J_{C-P}=9.6$ Hz) and 25.95 (CH_2, d, $^3J_{C-P}=9.6$ Hz) (cyclopentyl C3 and C4); ^{31}P NMR 52.2.

4.1.11. *trans*-(3,4-Epoxycyclopentyl)diphenylphosphine oxide 2b. To a cold (ice-bath) solution of the above mixture of **8b** and **9b** in the ratio of 1.8:1 (2.82 g, 10.6 mmol) in CH_2Cl_2 (50 mL), *m*-CPBA (8.9 g, 57% content, 29.4 mmol) was added and the mixture was stirred

at room temperature for 18 h. The solution was diluted with CH_2Cl_2 (50 mL), was washed with aqueous 10% $NaHSO_3$ (3×75 mL), H_2O (75 mL) and brine (75 mL). The organic phase was dried (Na_2SO_4), filtered and concentrated under reduced pressure to give a foamy yellow solid (2.72 g, 90%), mixture of **11b**,[13] **10b**[13] and **2b** in the approximate ratio of 1:4:9 (^{1}H NMR). To a solution of the above mixture (2.72 g, 9.58 mmol) in ethanol (150 mL) was added a solution of KOH in ethanol (4.3 mL, 1.6 M, 6.88 mmol) and the mixture was stirred at room temperature for 18 h. The solution was evaporated at reduced pressure to give a residue, which was dissolved in H_2O (50 mL). The solution was made acidic (pH 1) with 5N HCl and was extracted with CH_2Cl_2 (3×40 mL). The combined organic extracts were dried (Na_2SO_4), filtered and concentrated in vacuo to give a mixture of **2b** and **12b** (2.59 g, 95% yield) in the approximate ratio of 2:1 (^{1}H NMR) as a foamy brown solid. Standard column chromatography of the above mixture [silica gel (70 g), ethyl acetate] gave **2b** as a white solid (1.01 g, 52% overall yield from the amount of **8b** present in the mixture), **12b**[13] (780 mg, 73% overall yield from the amount of **9b** present in the mixture) and 240 mg of a mixture of **2b** and **12b**. An analytical sample of **2b** was obtained by crystallization (ethyl acetate), mp 120–121°C. IR (KBr) 1184, 1118 (P=O st) cm^{-1}; ^{1}H NMR 7.76–7.71 (m, 2H, Ar-H$_{ortho}$), 7.51–7.46 (m, 2H, Ar-H$_{para}$), 7.46–7.41 (m, 4H, Ar-H$_{meta}$), 3.53 (s, 2H, 3(4)-H), 2.64 (dtt, J=2.0 Hz, J'=8.0 Hz, J''=10.0 Hz, 1H, 1-H), 2.11 (dt, J=10.0 Hz, J'=14.5 Hz, 2H, 2(5)-H$_\alpha$), 2.01 (ddd, J=1.0 Hz, J'=8.0 Hz, J''=14.5 Hz, 2H, 2(5)-H$_\beta$); ^{13}C NMR 132.5 (C, d, $^1J_{C-P}$=97.7 Hz, Ar-C$_{ipso}$), 131.5 (CH, d, $^4J_{C-P}$=2.6 Hz, Ar-CH$_{para}$), 130.4 (CH, d, $^2J_{C-P}$=9.1 Hz, Ar-CH$_{ortho}$), 128.5 (CH d, $^3J_{C-P}$=11.6 Hz, Ar-CH$_{meta}$), 56.8 [CH, d, $^3J_{C-P}$=12.7 Hz, C3(4)], 31.0 (CH, d, $^1J_{C-P}$=76.5 Hz, C1), 27.8 [CH_2, s, C2(5)]; ^{31}P NMR 25.6; MS (EI), m/z (%): 285 [(M+H)$^+$, 2], 284 (M$^{\bullet+}$, 1), 283 [(M−H)$^+$, 4], 256 [(M−CO)$^{\bullet+}$, 17], 255 (23), 228 [(M−C_3H_4O)$^{\bullet+}$, 33], 202 (76), 201 [[PO(C_6H_5)$_2$]$^+$, 100]. Anal. calcd for: $C_{17}H_{17}O_2P$: C, 71.82; H, 6.03. Found: C, 71.90; H, 6.10%.

4.1.12. *trans*-(3,4-Epoxycyclopentyl)dicyclopentylphosphine oxide 2c. From a mixture of **8c** and **9c** in the ratio of 2.8:1 (23.4 g, 93 mmol) in CH_2Cl_2 (500 mL) and *m*-CPBA (58.4 g, 57%, 0.19 mol) and following a similar procedure to that described for **2b**, a mixture of **10c**,[13] **11c**[13] and **2c** (23.0 g, 93%) in the ratio of 1:2:7 (^{1}H NMR) was obtained. Flash column chromatography of the mixture [silica gel (270 g), ethyl acetate/methanol mixtures] gave a mixture of **10c** and **11c** (1.16 g), a mixture of the three epoxides (10.8 g) and **2c** (8.28 g) on elution with a mixture of ethyl acetate/methanol in the ratio of 95:5. The mixture of the three epoxides was submitted to a new flash column chromatography [silica gel (100 g), ethyl acetate/methanol mixtures] to give a mixture of **10c** and **11c** (2.68 g), a mixture of the three epoxides (2.42 g) and **2c** (4.01 g). Overall yield of **2c** from the amount of **8c** present in the starting mixture: 62%. Analytical data for **2c**: mp ≈25°C (wax at room temperature). IR (NaCl) 1186, 1143 (P=O st) cm^{-1}; ^{1}H NMR 3.52 [s, 2H, 3(4)-H], 2.16 [broad dd, J=8.0 Hz, J'=13.5 Hz, 2H, 2(5)-H$_\beta$], 2.10–2.00 [complex signal, 4H, cyclopentyl CH, 2(5)-H$_\alpha$ [δ 2.06, dt, J=10.5 Hz, J'=13.0 Hz]], 2.00–1.91 [m, 1H, 1-H], 1.90–1.80 (complex signal, 8H), 1.78–1.64 (complex signal, 4H) and 1.63–1.50 (complex signal, 4H) (cyclopentyl CH_2); ^{13}C NMR 56.5 [CH, d, $^3J_{C-P}$=11.2 Hz, C3(4)], 37.4 [CH, d, $^1J_{C-P}$=67.3 Hz, cyclopentyl C1], 29.6 [CH, d, $^1J_{C-P}$=65.8 Hz, C1], 28.7 [CH_2, broad s, C2(5)], 27.1 [CH_2, d, $^2J_{C-P}$=2.4 Hz, cyclopentyl C2 and C5], 26.2 (CH_2, d, $^3J_{C-P}$=10.2 Hz) and 26.1 (CH_2, d, $^3J_{C-P}$=10.1 Hz) [cyclopentyl C3 and C4]; ^{31}P NMR 51.3. MS (EI), m/z (%): 268 (M$^{\bullet+}$, 2), 267 [(M−H)$^+$, 3], 200 [(M−C_5H_8)$^{\bullet+}$, 18], 186 [[HPO(C_5H_9)$_2$]$^{\bullet+}$, 10], 134 (47), 67 (100). Anal. calcd for: $C_{15}H_{25}O_2P$·0.6H_2O: C, 64.54; H, 9.47. Found: C, 64.58; H, 9.59%.

4.1.13. *c*-4-(Diisopropylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentyl acetate 14a and *t*-4-(diisopropylphosphinoyl) - *t* - 2 - [(diphenylphosphinoyl)-methyl]-*r*-1-cyclopentyl acetate 17a

4.1.13.1. Mixture of alcohols 13a and 16a. To a cold solution (ice-bath) of methyldiphenylphosphine oxide (220 mg, 1.00 mmol) in anhydrous THF (3.0 mL) was added dropwise *n*-butyllithium (0.75 mL, 1.6 M in hexanes, 1.2 mmol). The suspension was cooled to −78°C and a solution of anhydrous epoxide **2a** (216 mg, 1.00 mmol, azeotropic distillation of the water content with toluene in a Dean–Stark equipment) in anhydrous toluene (1 mL) was added dropwise. The mixture was allowed to warm to room temperature for 3 h, and then was heated under reflux for 15 h. The mixture was allowed to cool to room temperature, saturated aqueous solution of NH_4Cl (6 mL) was added, and the organic phase was separated and evaporated to dryness in vacuo. The residue was dissolved in water (15 mL) and extracted with CH_2Cl_2 (3×30 mL). The combined organic phases were dried (Na_2SO_4) and concentrated in vacuo to give a dark oily residue (410 mg). Flash column chromatography of the above solid [silica gel (21 g), ethyl acetate/methanol mixtures] gave a mixture of **13a** and **16a** (270 mg, 62%) in a ratio of 3:1 (^{1}H NMR). Attempted separation of a mixture of these alcohols from a higher scale batch, gave only mixtures of these alcohols in different ratio.

4.1.13.2. Acetylation of the mixture of 13a and 16a. A solution of a mixture of **13a** and **16a** [in the ratio of 65:35 (HPLC), 800 mg, 1.85 mmol] in acetic anhydride (9.5 mL) was heated under reflux for 2 h. The solution was allowed to cool to room temperature and then evaporated to dryness. The residue was dissolved in CH_2Cl_2 (80 mL) and was washed with H_2O (3×40 mL). The organic phase was dried (Na_2SO_4), filtered and concentrated in vacuo to give a solid residue (820 mg). Flash column chromatography of the above solid [silica gel (90 g), ethyl acetate/methanol mixtures] gave pure **17a** (200 mg), a mixture of **14a** and **17a** (160 mg) and pure **14a** (350 mg, 81% overall yield). Analytical samples of **14a** and **17a** were obtained by crystallization from ethyl acetate.

4.1.13.3. Analytical and spectroscopic data for 14a. Mp 158.5–159.5°C (ethyl acetate). IR (KBr) 1726 (C=O

st), 1178, 1149 (PO st) cm^{-1}; ^1H NMR 7.75–7.70 (complex signal, 4H, Ar-H_{ortho}), 7.53–7.41 (complex signal, 6H, Ar-H_{meta}, Ar-H_{para}), 4.78 (pseudo q, $J=6.5$ Hz, 1H, 1-H), 2.57 (ddd, $J=4.0$ Hz, $J''=10.5$ Hz, $J'''=14.5$ Hz, 1H, $CH_{syn}P$), 2.41 (m, 1H, 2-H), 2.34–2.20 (complex signal, 3H, 3-H_α, 4-H and 5-H_β), 2.15 (ddd, $J=$ 10.5 Hz, $J'=13.0$ Hz, $J''=15.0$ Hz, 1H, $CH_{anti}P$), 2.06–1.93 [complex signal, 5H, 2 C$\underline{H}(CH_3)_2$ and 1.97 (s, $OCOCH_3$)], 1.94–1.78 (complex signal, 2H, 3-H_β, 5-H_α), 1.14 (dd, $J=7.5$ Hz, $J'=15.0$ Hz, 6H), 1.13 (dd, $J=7.5$ Hz, $J'=14.0$ Hz, 3H) and 1.12 (dd, $J=7.5$ Hz, $J'=15.0$ Hz, 3H) [2 $CH(C\underline{H}_3)_2$]; ^{13}C NMR 171.0 (C, s, O$\underline{C}OCH_3$), 133.7 (C, d, $^1J_{C-P}=93.6$ Hz) and 132.4 (C, d, $^1J_{C-P}=94.0$ Hz) (Ar-C_{ipso}), 131.8 (CH, d, $^4J_{C-P}=3.0$ Hz) and 131.7 (CH, d, $^4J_{C-P}=2.6$ Hz) (Ar-CH_{para}), 130.7 (CH, d, $^2J_{C-P}=9.1$ Hz) and 130.5 (CH, d, $^2J_{C-P}=$ 9.7 Hz) (Ar-CH_{ortho}), 128.7 (CH, d, $^3J_{C-P}=11.7$ Hz) and 128.6 (CH, d, $^3J_{C-P}=11.7$ Hz) (Ar-CH_{meta}), 80.5 (CH, dd, $^3J_{C-P}=10.4$ Hz, $^3J_{C-P}=14.4$ Hz, C1), 38.8 (CH, dd, $^2J_{C-P}=3.5$ Hz, $^3J_{C-P}=6.0$ Hz, C2), 32.7 [CH_2, d, $^1J_{C-P}=71.4$ Hz, CH_2P], 31.3 (CH_2, d, $^2J_{C-P}=2.6$ Hz, C5), 29.8 (CH, d, $^1J_{C-P}=62.8$ Hz, C4), 29.3 (CH_2, pseudo t, $^2J_{C-P}=^3J_{C-P}=2.5$ Hz, C3), 26.2 (CH, d, $^1J_{C-P}=62.3$ Hz) and 25.9 (CH, d, $^1J_{C-P}=62.8$ Hz) [2 $C\underline{H}(CH_3)_2$], 21.1 (CH_3, s, $OCOC\underline{H}_3$), 16.8 (CH_3, d, $^2J_{C-P}=2.0$ Hz), 16.7 (CH_3, d, $^2J_{C-P}=2.6$ Hz), 16.6 (CH_3, d, $^2J_{C-P}=2.5$ Hz) and 16.5 (CH_3, d, $^2J_{C-P}=2.5$ Hz) [2 $CH(C\underline{H}_3)_2$]; ^{31}P NMR 56.9 [$PO(i\text{-}Pr)_2$], 30.4 [$PO(C_6H_5)_2$]; MS (EI), m/z (%): 475 [$(M+H)^+$, 2], 474 ($M^{\bullet+}$, 2), 415 [$(M-CH_3COO)^+$, 8], 389 [$(M-CH_3CO-C_3H_6)^+$, 39], 341 [$[M-(i\text{-}Pr)_2PO]^+$, 34], 281 [$[M-CH_3COOH-(i\text{-}Pr)_2PO]^+$, 65], 215 [$[CH_2PO(C_6H_5)_2]^+$, 14], 201 [$[PO(C_6H_5)_2]^+$, 100]. Anal. calcd for $C_{26}H_{36}O_4P_2$: C, 65.81; H, 7.65. Found: C, 65.63; H, 7.86%.

4.1.13.4. Analytical and spectroscopic data for 17a. Mp 184.5–185.5°C (ethyl acetate). IR (KBr) 1731 (C=O st), 1168, 1147 (P=O st) cm^{-1}; ^1H NMR 7.79–7.71 (complex signal, 4H, Ar-H_{ortho}), 7.51–7.41 (complex signal, 6H, Ar-H_{meta}, Ar-H_{para}), 4.90 (ddd, $J=3.5$ Hz, $J'=5.5$ Hz, $J''=7.0$ Hz, 1H, 1-H), 2.64 [ddd, $J=3.0$ Hz, $J'=13.0$ Hz, $J''=14.5$ Hz, 1H, CH_{syn}-P], 2.52 (m, 1H, 2-H), 2.45–2.34 [complex signal, 2H, 5-H_β, CH_{anti}-P], 2.27 (tt, $J=10.0$ Hz, $J'=10.5$ Hz, 1H, 4-H), 2.03–1.82 [complex signal, 6H, 3-H_α, 2 C$\underline{H}(CH_3)_2$ and 1.96 (s, 3H, $OCOCH_3$)], 1.77 (m, 1H, 5-H_α), 1.49 (tt, $J=10.0$ Hz, $J'=11.0$ Hz, 1H, 3-H_β), 1.14 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H) and 1.13 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H) [$[CH(C\underline{H}_3)_2]_b$], 1.06 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H) and 0.99 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H) [$[CH(C\underline{H}_3)_2]_a$]; ^{13}C NMR 170.6 (C, s, O$\underline{C}OCH_3$), 133.3 (C, d, $^1J_{C-P}=97.6$ Hz) and 133.2 (C, d, $^1J_{C-P}=98.8$ Hz) (Ar-C_{ipso}), 131.7 (CH, d, $^4J_{C-P}=2.4$ Hz) and 131.6 (CH, d, $^4J_{C-P}=3.0$ Hz) (Ar-CH_{para}), 130.8 (CH, d, $^2J_{C-P}=9.8$ Hz) and 130.6 (CH, d, $^2J_{C-P}=9.1$ Hz) (Ar-CH_{ortho}), 128.7 (CH, d, $^3J_{C-P}=11.6$ Hz) and 128.6 (CH, d, $^3J_{C-P}=11.6$ Hz) (Ar-CH_{meta}), 81.1 (CH, dd, $^3J_{C-P}=8.5$ Hz, $^3J_{C-P}=14.6$ Hz, C1), 40.2 (CH, dd, $^2J_{C-P}=4.0$ Hz, $^3J_{C-P}=8.9$ Hz, C2), 32.8 [CH_2, d, $^1J_{C-P}=70.7$ Hz, CH_2P], 32.2 (CH_2, t, $^2J_{C-P}=^3J_{C-P}=2.4$ Hz, C3), 31.9 (CH, d, $^1J_{C-P}=62.8$ Hz, C4), 31.7 (CH_2, d, $^2J_{C-P}=2.4$ Hz, C5), 26.4 [CH, d, $^1J_{C-P}=62.8$ Hz, $[C\underline{H}(CH_3)_2]_b$], 26.0 [CH, d, $^1J_{C-P}=62.8$ Hz, $[C\underline{H}(CH_3)_2]_a$], 21.1 ($CH_3$, s, $OCOC\underline{H}_3$), 16.8 (CH_3, d, $^2J_{C-P}=2.4$ Hz) and 16.7 (CH_3, d, $^2J_{C-P}=2.4$ Hz) [$[CH(C\underline{H}_3)_2]_b$], 16.6 ($CH_3$, d, $^2J_{C-P}=2.5$ Hz) and 16.5 (CH_3, d, $^2J_{C-P}=2.4$ Hz) [$[CH(C\underline{H}_3)_2]_a$]; ^{31}P NMR 56.3 [$PO(i\text{-}Pr)_2$], 30.3 [$PO(C_6H_5)_2$]; MS (EI), m/z (%): 475 [$(M+H)^+$, 5], 474 ($M^{\bullet+}$, 3), 431 [$(M-CH_3CO)^+$, 25], 389 [$(M-CH_3CO-C_3H_6)^+$, 32], 341 [$[M-(i\text{-}Pr)_2PO]^+$, 74], 281 [$[M-CH_3COOH-(i\text{-}Pr)_2PO]^+$, 70], 201 [$[PO(C_6H_5)_2]^+$, 100]. Anal. calcd for $C_{26}H_{36}O_4P_2$: C, 65.81; H, 7.65. Found: C, 65.63; H, 7.61%.

4.1.14. *c*-4-(Diphenylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentyl acetate 14b and *t*-4-(diphenylphosphinoyl) - *t* - 2 - [(diphenylphosphinoyl)methyl]-*r*-1-cyclopentyl acetate 17b

4.1.14.1. Mixture of alcohols 13b and 16b. From methyldiphenylphosphine oxide (472 mg, 98% content, 2.14 mmol) in anhydrous THF (12 mL), *n*-butyllithium (2.14 mL, 1.6 M in hexanes, 3.42 mmol) and anhydrous epoxide **2b** (607 mg, 2.14 mmol, azeotropic distillation of the water content with toluene in a Dean–Stark equipment) in anhydrous THF (21 mL), and following the above described procedure for **2a**, a mixture of **13b** and **16b** in the ratio of 3:2 (^1H NMR) was obtained as a foamy brown solid (960 mg, 90%), which could neither be separated by column chromatography nor by crystallization.

4.1.14.2. Acetylation of the mixture of 13b and 16b. From a mixture of **13b** and **16b** in the ratio of 3:2 (1.12 g, 2.25 mmol) and acetic anhydride (9.5 mL) and following a similar procedure to that described above for the mixture of **13a** and **16a**, a mixture of acetates **14b** and **17b** (1.15 g) was obtained. Flash column chromatography of the above mixture [silica gel (100 g), ethyl acetate/methanol mixtures] gave pure **17b** (350 mg, 30% overall yield from **2b**), a mixture of **14b** and **17b** (60 mg) and pure **14b** (470 mg, 41% overall yield from **2b**). Analytical samples of **14b** and **17b** were obtained by crystallization (ethyl acetate).

4.1.14.3. Analytical and spectroscopic data for 14b. Mp 233.5–234°C (ethyl acetate). IR (KBr) 1725 (C=O st), 1181, 1119 (P=O st) cm^{-1}; ^1H NMR 7.71–7.62 (complex signal, 8H, Ar-H_{ortho}), 7.51–7.37 (complex signal, 12H, Ar-H_{meta}, Ar-H_{para}), 4.77 (q, $J=7.5$ Hz, 1H, 1-H), 2.89–2.80 (m, 1H, 4-H), 2.54 (ddd, $J=4.0$ Hz, $J'=10.5$ Hz, $J''=15.0$ Hz, 1H, CH_{syn}-P), 2.48–2.38 (m, 1H, 2-H), 2.31–2.19 (complex signal, 2H, 3-H_α, 5-H_β), 2.15 (ddd, $J=10.0$ Hz, $J'=12.5$ Hz, $J''=15.0$ Hz, 1H, CH_{anti}-P), 1.92 (s, 3H, CH_3), 1.86 (dddd, $J=8.5$ Hz, $J'=10.5$ Hz, $J''=13.5$ Hz, $J'''=18.0$ Hz, 1H, 5-H_α), 1.73 (pseudo ddt, $J=8.0$ Hz, $J'=14.0$ Hz, $J''=10.0$ Hz, 1H, 3-H_β); ^{13}C NMR 170.8 (C, s, C=O), 133.4 (C, d, $^1J_{C-P}=98.2$ Hz), 132.4 (C, d, $^1J_{C-P}=98.2$ Hz), 132.3 (C, d, $^1J_{C-P}=98.2$ Hz) and 131.8 (C, d, $^1J_{C-P}=98.2$ Hz) (Ar-C_{ipso}), 131.7 (CH, d, $^4J_{C-P}=1.5$ Hz) and 131.6 (CH, d, $^4J_{C-P}=1.5$ Hz) (Ar-CH_{para}), 130.9 (CH, d, $^2J_{C-P}=9.1$ Hz), 130.7 (CH, d, $^2J_{C-P}=8.1$ Hz), 130.6 (CH, d, $^2J_{C-P}=8.6$ Hz) and 130.4 (CH, d, $^2J_{C-P}=9.1$ Hz) (Ar-CH_{ortho}), 128.6 (CH, d, $^3J_{C-P}=11.2$ Hz) and 128.5 (CH, d, $^3J_{C-P}=11.2$ Hz) (Ar-CH_{meta}),

80.1 (CH, dd, $^3J_{C-P}=10.6$ Hz, $^3J'_{C-P}=13.7$ Hz, C1), 38.8 (CH, pseudo t, $^2J_{C-P}=^3J_{C-P}=4.1$ Hz, C2), 33.1 (CH, d, $^1J_{C-P}=75.0$ Hz, C4), 32.6 (CH_2, d, $^1J_{C-P}=71.4$ Hz, CH_2-P), 30.4 (CH_2, s, C5), 28.8 (CH_2, s, C3), 21.0 (CH_3, s, $\underline{C}H_3COO$); ^{31}P NMR 31.7 [Cy-PO(C_6H_5)$_2$], 28.0 [$CH_2PO(C_6H_5)_2$]. MS (EI), m/z (%): 542 ($M^{\bullet+}$, 6), 483 [(M−CH_3COO)$^+$, 6], 341 [[M−PO(C_6H_5)$_2$]$^+$, 30], 281 [[M−PO(C_6H_5)$_2$−AcOH]$^+$, 48], 202 (28), 201 [[PO(C_6H_5)$_2$]$^+$, 100]. Anal. calcd for: $C_{32}H_{32}O_4P_2$: C, 70.84; H, 5.92. Found: C, 70.65; H, 5.86%.

4.1.14.4. Analytical and spectroscopic data for 17b. Mp 239–239.5°C (ethyl acetate). IR (KBr) 1721 (C=O st), 1181, 1119 (P=O st) cm^{-1}; ^{1}H NMR 7.74–7.66 (complex signal, 6H) and 7.58–7.53 (m, 2H) (Ar-H_{ortho}), 7.50–7.31 (complex signal, 12H, Ar-H_{meta}, Ar-H_{para}), 4.92 (ddd, $J=4.0$ Hz, $J'=5.5$ Hz, $J''=7.0$ Hz, 1H, 1-H), 2.84 (d quint, $J=2.0$ Hz, $J'=9.5$ Hz, 1H, 4-H), 2.62–2.53 (complex signal, 2H, 2-H, CH_{syn}-P), 2.44–2.34 (complex signal, 2H, 5-H$_\beta$ and CH_{anti}-P), 1.93 (s, 3H, CH_3COO), 1.86 (m, 1H, 3-H$_\alpha$), 1.69 (dddd, $J=4.5$ Hz, $J'=5.5$ Hz, $J''=9.5$ Hz, $J'''=14.0$ Hz, 1H, 5-H$_\alpha$), 1.51 (ddt, $J=13.5$ Hz, $J'=15.0$ Hz, $J''=9.0$ Hz, 1H, 3-H$_\beta$); ^{13}C NMR 170.3 (C, s, CO), 133.2 (C, d, $^1J_{C-P}=$ 98.7 Hz) and 132.9 (C, d, $^1J_{C-P}=97.7$ Hz), 133.0 and 132.8 (C, higher δ signals of two d) (Ar-C_{ipso}), 131.7 (CH, broad s) and 131.5 (CH, broad s) (Ar-CH_{para}), 130.7 (CH, d, $^2J_{C-P}=9.1$ Hz) and 130.5 (CH, d, $^2J_{C-P}=$ 9.1 Hz) (Ar-CH_{ortho}), 128.6 (CH, d, $^3J_{C-P}=11.6$ Hz) and 128.4 (CH, d, $^3J_{C-P}=11.7$ Hz) (Ar-CH_{meta}), 81.1 (CH, dd, $^3J_{C-P}=8.7$ Hz, $^3J'_{C-P}=14.2$ Hz, C1), 40.0 (CH, dd, $^2J_{C-P}=3.5$ Hz, $^3J_{C-P}=8.6$ Hz, C2), 35.4 (CH, d, $^1J_{C-P}=75.9$ Hz, C4), 32.6 (CH_2, d, $^1J_{C-P}=71.4$ Hz, CH_2-P), 31.0 (CH_2, s, C3), 30.9 (CH_2, s, C5), 21.1 (CH_3, s, $\underline{C}H_3COO$); ^{31}P NMR 30.8 [Cy-PO(C_6H_5)$_2$], 28.0 [$CH_2PO(C_6H_5)_2$]; MS (EI), m/z (%): 542 ($M^{\bullet+}$, 3), 483 [(M−CH_3COO)$^+$, 4], 341 [[M−PO(C_6H_5)$_2$]$^+$, 54], 281 [[M−PO(C_6H_5)$_2$−CH_3COOH]$^+$, 40], 215 [[$CH_2PO(C_6H_5)_2$]$^+$, 11], 202 (28), 201 [[PO(C_6H_5)$_2$]$^+$, 100]. Anal. calcd for: $C_{32}H_{32}O_4P_2$: C, 70.84; H, 5.92. Found: C, 70.93; H, 5.80%.

4.1.15. *c*-4-(Dicyclopentylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentyl acetate 14c and *t*-4-(dicyclopentylphosphinoyl) - *t* - 2 - [(diphenylphosphinoyl)-methyl]-*r*-1-cyclopentyl acetate 17c

4.1.15.1. Mixture of alcohols 13c and 16c. From methyldiphenylphosphine oxide (716 mg, 3.3 mmol) in anhydrous THF (100 mL), *n*-butyllithium (3.25 mL, 1.6 M in hexanes, 5.2 mmol) and anhydrous epoxide **2c** (870 mg, 3.25 mmol, azeotropic distillation of the water content with toluene in a Dean–Stark equipment) in anhydrous THF (150 mL), and following the above described procedure for **2a**, a mixture of **13c** and **16c** (in the ratio of 2.5:1, ^{1}H NMR) was obtained as a foamy brown solid (1.16 g, 74%), which could not be separated by column chromatography nor by crystallization.

4.1.15.2. Acetylation of the mixture of 13c and 16c. From a solution of a mixture of **13c** and **16c** (860 mg, 1.77 mmol) in acetic anhydride (13.4 mL) and following a similar procedure to that described for the mixture of **13a** and **16a**, a mixture of **14c** and **17c** (920 mg) was obtained. Flash column chromatography of the above mixture [silica gel (70 g), ethyl acetate/methanol mixtures] gave, on elution with a mixture of ethyl acetate/methanol in the ratio of 92:8 and in order of elution: pure **17c** (120 mg), a mixture of **14c** and **17c** (250 mg) and pure **14c** (200 mg). The overall yield of **14c** plus **17c** from starting **2c** was 45.5% (9.5% of pure **14c**, 16% of pure **17c** and 20% of a mixture of **14c** and **17c**). Analytical samples of **14c** and **17c** were obtained by crystallization (ethyl acetate).

4.1.15.3. Analytical and spectroscopic data for 14c. Mp 197–198°C (ethyl acetate). IR (KBr) 1730 (C=O st), 1179, 1121 (P=O st) cm^{-1}; ^{1}H NMR 7.75–7.69 (complex signal, 4H, Ar-H_{ortho}), 7.53–7.41 (complex signal, 6H, Ar-H_{meta}, Ar-H_{para}), 4.78 (pseudo q, $J=7.0$ Hz, 1H, 1-H), 2.56 (ddd, $J=3.5$ Hz, $J'=10.5$ Hz, $J''=14.5$ Hz, 1H, $C\underline{H}_{syn}$-P), 2.43–2.10 (complex signal, 5H, 2-H, 3-H$_\alpha$, 4-H, 5-H$_\beta$, CH_{anti}-P), 2.02–1.91 (complex signal, 2H, cyclopentyl CH), 1.98 (s, 3H, CH_3COO), 1.87–1.60 (complex signal, 14H) and 1.57–1.45 (complex signal, 4H) (cyclopentyl CH_2, 3-H$_\beta$, 5-H$_\alpha$); ^{13}C NMR 170.7 (C, s, CO), 133.5 (C, d, $^1J_{C-P}=98,7$ Hz) and 133.1 (C, higher δ signal of a d) (Ar-C_{ipso}), 131.7 (CH, d, $^4J_{C-P}=$ 2.5 Hz) and 131.6 (CH, d, $^4J_{C-P}=2.5$ Hz) (Ar-CH_{para}), 130.6 (CH, d, $^2J_{C-P}=9.1$ Hz) and 130.4 (CH, d, $^2J_{C-P}=$ 9.1 Hz) (Ar-CH_{ortho}), 128.6 (CH, d, $^3J_{C-P}=11.1$ Hz) and 128.5 (CH, d, $^3J_{C-P}=11.7$ Hz) (Ar-CH_{meta}), 80.4 (CH, dd, $^3J_{C-P}=10.6$ Hz, $^3J'_{C-P}=14.2$ Hz, C1), 38.7 (CH, dd, $^2J_{C-P}=3.5$ Hz, $^3J_{C-P}=6.6$ Hz, C2), 36.9 (CH, d, $^1J_{C-P}=66.8$ Hz) and 36.6 (CH, d, $^1J_{C-P}=66.7$ Hz) (cyclopentyl CH), 32.56 (CH_2, d, $^1J_{C-P}=69.9$ Hz, CH_2-P), 32.5 (CH, d, $^1J_{C-P}=65.8$ Hz, C4), 31.6 (CH_2, s, C5), 29.5 (CH_2, s, C3), 27.2 (CH_2, broad s), 27.01 (CH_2, broad s) and 26.95 (2 CH_2, broad s) (cyclopentyl C2 and C5), 26.10 (CH_2, d, $^3J_{C-P}=9.7$ Hz), 26.05 (CH_2, d, $^3J_{C-P}=10.1$ Hz) and 26.01 (2 CH_2, d, $^3J_{C-P}=9.7$ Hz) (cyclopentyl C3 and C4), 21.0 (CH_3, s, $\underline{C}H_3COO$); ^{31}P NMR 51.2 [PO(C_5H_9)$_2$], 28.0 [PO(C_6H_5)$_2$]; MS (EI), m/z (%): 467 [(M−CH_3COO)$^+$, 4], 389 [(M−C_5H_8−C_5H_9)$^+$, 31], 341 [(M−PO(C_5H_9)$_2$)$^+$, 24], 281 [[M−PO(C_5H_9)$_2$−CH_3COOH]$^+$, 59], 265 [[M−PO(C_6H_5)$_2$−CH_3COOH]$^+$, 17], 215 [[$CH_2PO(C_6H_5)_2$]$^+$, 14], 201 [[PO(C_6H_5)$_2$]$^+$, 100], 185 [[PO(C_5H_9)$_2$]$^+$, 16]. Anal. calcd for: $C_{30}H_{40}O_4P_2$: C, 68.42; H, 7.66. Found: C, 68.17; H, 7.68%.

4.1.15.4. Analytical and spectroscopic data for 17c. Mp 200–200.5°C (ethyl acetate). IR (KBr) 1722 (C=O st), 1181, 1162, 1120 (P=O st) cm^{-1}; ^{1}H NMR 7.78–7.70 (complex signal, 4H, Ar-H_{ortho}), 7.51–7.41 (complex signal, 6H, Ar-H_{meta}, Ar-H_{para}), 4.89 (ddd, $J=3.0$ Hz, $J'=5.5$ Hz, $J''=8.0$ Hz, 1H, 1-H), 2.71 (ddd, $J=2.7$ Hz, $J'=12.5$ Hz, $J''=15.0$ Hz, 1H, CH_{syn}-P), 2.52–2.44 (m, 1H, 2-H), 2.44–2.36 (m, 1H, 5-H$_\beta$), 2.33 (ddd, $J=9.0$ Hz, $J'=10.5$ Hz, $J''=15.0$ Hz, 1H, CH_{anti}-P), 2.24–2.16 (m, 1H, 4-H), 2.02–1.38 [complex signal, 24H, cyclopentyl CH and CH_2, 3-H$_\alpha$, 3-H$_\beta$, 5-H$_\alpha$, CH_3COO (s, 1.97)]; ^{13}C NMR 170.5 (C, s, CO), 133.2 (C, d, $^1J_{C-P}=97.7$ Hz) and 133.1 (C, d, $^1J_{C-P}=97.8$ Hz) (Ar-C_{ipso}), 131.6 (CH, d, $^4J_{C-P}=2.2$ Hz) and 131.5 (CH, d, $^4J_{C-P}=2.2$ Hz) (Ar-CH_{para}), 130.7 (CH, d, $^2J_{C-P}=9.3$

Hz) and 130.4 (CH, d, $^2J_{C-P}=9.3$ Hz) (Ar-CH_{ortho}), 128.6 (CH, d, $^3J_{C-P}=11.5$ Hz) and 128.5 (CH, d, $^3J_{C-P}=11.5$ Hz) (Ar-CH_{meta}), 80.9 (CH, dd, $^3J_{C-P}=9.3$ Hz, $^3J'_{C-P}=14.8$ Hz, C1), 40.5 (CH, dd, $^2J_{C-P}=3.5$ Hz, $^3J_{C-P}=9.6$ Hz, C2), 37.5 (CH, d, $^1J_{C-P}=66.9$ Hz) and 36.9 (CH, d, $^1J_{C-P}=66.9$ Hz) (cyclopentyl CH), 34.9 (CH, d, $^1J_{C-P}=65.8$ Hz, C4), 32.9 (CH_2, d, $^1J_{C-P}=71.3$ Hz, CH_2-P), 32.9 (CH_2, s, C3), 32.0 (CH_2, broad s, C5), 27.2 (CH_2, broad s), 27.1 (CH_2, broad s), 27.0 (CH_2, broad s) and 26.8 (CH_2, broad s) (cyclopentyl C2 and C5), 26.13 (CH_2, d, $^3J_{C-P}=9.9$ Hz), 26.10 (CH_2, d, $^3J_{C-P}=9.7$ Hz), 26.05 (CH_2, d, $^3J_{C-P}=9.9$ Hz) and 26.01 (CH_2, d, $^3J_{C-P}=9.9$ Hz) (cyclopentyl C3 and C4), 21.1 (CH_3, s, CH_3COO); ^{31}P NMR 50.8 [$PO(C_5H_9)_2$], 27.9 [$PO(C_6H_5)_2$]; MS (EI), m/z (%): 526 ($M^{\bullet+}$, 1), 467 [$(M-CH_3COO)^+$, 7], 389 [$(M-C_5H_8-C_5H_9)^+$, 84], 341 [$[M-PO(C_5H_9)_2]^+$, 75], 281 [$[M-PO(C_5H_9)_2-CH_3COOH]^+$, 73], 215 [$[CH_2PO(C_6H_5)_2]^+$, 15], 201 [$[PO(C_6H_5)_2]^+$, 100], 185 [$[PO(C_5H_9)_2]^+$, 15]. Anal. calcd for: $C_{30}H_{40}O_4P_2$: C, 68.42; H, 7.66. Found: C, 68.24; H, 7.81%.

4.1.16. *c*-4-(Diisopropylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol 13a. To a solution of **14a** (1.03 g, 2.2 mmol) in methanol (30 mL) was added solid $NaOCH_3$ (227 mg, 4.2 mmol) and the solution was heated under reflux for 2 h. The mixture was allowed to cool to room temperature and the solvent was evaporated to dryness. The residue was dissolved in CH_2Cl_2 (100 mL) and the solution was washed with saturated aqueous solution of NH_4Cl (2×30 mL). The organic phase was dried (Na_2SO_4) and concentrated in vacuo to give **13a** as a very hygroscopic foamy white solid (880 mg, 94%), which could not be crystallized. IR (KBr, film) 3334 (OH st), 1169 (P=O st) cm^{-1}; ^{1}H NMR 7.73–7.68 (complex signal, 4H, Ar-H_{ortho}), 7.53–7.49 (complex signal, 2H, Ar-H_{para}), 7.48–7.43 (complex signal, 4H, Ar-H_{meta}), 3.93 (pseudo q, $J=7.5$ Hz, 1H, 1-H), 2.49–2.38 [complex signal, 2H, 3-H_α and CH_{syn}P [δ 2.42, ddd, $J=4.0$ Hz, $J'=11.0$ Hz, $J''=15.0$ Hz]], 2.35 (m, 1H, 4-H), 2.24 [ddd, $J=9.5$ Hz, $J'=13.5$ Hz, $J''=15.0$ Hz, 1H, CH_{anti}P], 2.19 (ddt, $J=5.5$ Hz, $J'=7.5$ Hz, $J''=13.0$ Hz, 1H, 5-H_β), 2.14–1.97 [complex signal, 3H, 2 $CH(CH_3)_2$ and 2-H], 1.94 (dddd, $J=8.5$ Hz, $J'=10.0$ Hz, $J''=12.5$ Hz, $J'''=14.0$ Hz, 1H, 5-H_α), 1,74 (ddt, $J=8.0$ Hz, $J'=10.5$ Hz, $J''=13.0$ Hz, 1H, 3-H_β), 1.17 (dd, $J=7.2$ Hz, $J'=14.3$ Hz, 3H), 1.15 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H), 1.146 (dd, $J=7.0$ Hz, $J'=14.3$ Hz, 3H), 1.14 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H) [2 $CH(CH_3)_2$]; ^{13}C NMR 132.3 (C, d, $^1J_{C-P}=101.1$ Hz) and 131.2 (C, d, $^1J_{C-P}=100.3$ Hz) (Ar-C_{ipso}), 132.0 (CH, d, $^4J_{C-P}=2.5$ Hz, Ar-CH_{para}), 130.8 (CH, d, $^2J_{C-P}=9.6$ Hz) and 130.4 (CH, d, $^2J_{C-P}=9.1$ Hz) (Ar-CH_{ortho}), 128.8 (CH, d, $^3J_{C-P}=12.2$ Hz) and 128.7 (CH, d, $^3J_{C-P}=11.6$ Hz) (Ar-CH_{meta}), 78.2 (CH, dd, $^2J_{C-P}=4.5$ Hz, $^3J_{C-P}=9.7$ Hz, C1), 41.5 (CH, pseudo t, $^2J_{C-P}=^4J_{C-P}=3.8$ Hz, C2), 34.6 (CH_2, d, $^2J_{C-P}=3.0$ Hz, C5), 34.58 (CH_2, d, $^1J_{C-P}=69.9$ Hz, CH_2P), 31.4 (CH_2, dd, $^2J_{C-P}=3.3$ Hz, $^3J_{C-P}=13.4$ Hz, C3), 28.9 (CH, d, $^1J_{C-P}=61.7$ Hz, C4), 25.8 (CH, d, $^1J_{C-P}=62.8$ Hz) and 25.6 (CH, d, $^1J_{C-P}=62.3$ Hz) [2 $CH(CH_3)_2$], 16.73 (CH_3, d, $^2J_{C-P}=2.6$ Hz), 16.67 (CH_3, d, $^2J_{C-P}=2.0$ Hz), 16.6 (CH_3, d, $^2J_{C-P}=2.6$ Hz) and 16.4 (CH_3, d, $^2J_{C-P}=2.6$ Hz) [2 $CH(CH_3)_2$]; ^{31}P NMR 59.2 [$PO(i\text{-}Pr)_2$], 35.5 [$PO(C_6H_5)_2$]; MS (EI), m/z (%): 433 [$(M+H)^+$, 4], 432 ($M^{\bullet+}$, 2), 347 [$(M-C_3H_6-C_3H_7)^+$, 5], 299 [$(M-(i\text{-}Pr)_2PO]^+$, 33], 281 [$[M-H_2O-(i\text{-}Pr)_2PO]^+$, 13], 231 [$[M-PO(C_6H_5)_2]^+$, 100], 215 [$[CH_2PO(C_6H_5)_2]^+$, 11], 201 [$[PO(C_6H_5)_2]^+$, 59]. Anal. calcd for $C_{24}H_{34}O_3P_2\cdot 2.5H_2O$: C, 60.36; H, 8.24. Found: C, 60.09; H, 8.17%.

4.1.17. *c*-4-(Diphenylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol 13b. From a solution of **14a** (890 mg, 1.64 mmol) in methanol (60 mL) and $NaOCH_3$ (195 mg, 3.6 mmol) and following the procedure described for **13a**, **13b** (820 mg, quantitative yield) was obtained as a foamy brown solid. An analytical sample of **13b** was obtained by crystallization, mp 108–108.5°C (ethyl acetate). IR (KBr) 3380 (OH st), 1174, 1119 (P=O st) cm^{-1}; ^{1}H NMR 7.73–7.64 (complex signal, 8H, Ar-H_{ortho}), 7.53–7.37 (complex signal, 12H, Ar-H_{para}, Ar-H_{meta}), 3.96 (pseudo q, $J=7.0$ Hz, 1H, 1-H), 2.96–2.87 (m, 1H, 4-H), 2.39–2.28 [complex signal, 2H, 3-H_α and CH_{syn}-P [δ 2.36 (ddd, $J=5.0$ Hz, $J'=10.5$ Hz, $J''=14.5$ Hz)]], 2.20 (ddd, $J=9.0$ Hz, $J'=13.0$ Hz, $J''=15.0$ Hz, 1H, CH_{anti}-P), 2.18–2.07 (complex signal, 2H, 2-H and 5-H_β), 1.98 (dddd, $J=8.5$ Hz, $J'=9.0$ Hz, $J''=13.0$ Hz, $J'''=17.5$ Hz, 1H, 5-H_α), 1.78 (ddt, $J=7.5$ Hz, $J'=13.5$ Hz, $J''=11.0$ Hz, 1H, 3-H_β); ^{13}C NMR 133.0 (C, higher δ signal of a d), 132.05 (C, higher δ signal of a d), 132.05 (C, d, $^1J_{C-P}=97.2$ Hz) and 131.95 (C, d, $^1J_{C-P}=97.2$ Hz) (Ar-C_{ipso}), 132.0 (2 CH, d, $^4J_{C-P}=2.5$ Hz), 131.7 (CH, d, $^4J_{C-P}=4.1$ Hz) and 131.6 (CH, d, $^4J_{C-P}=3.0$ Hz) (Ar-CH_{para}), 130.92 (CH, d, $^2J_{C-P}=9.1$ Hz), 130.88 (CH, d, $^2J_{C-P}=9.1$ Hz), 130.8 (CH, d, $^2J_{C-P}=9.7$ Hz) and 130.5 (CH, d, $^2J_{C-P}=9.7$ Hz) (Ar-CH_{ortho}), 128.8 (CH, d, $^3J_{C-P}=11.6$ Hz), 128.7 (CH, d, $^3J_{C-P}=11.6$ Hz), 128.6 (CH, d, $^3J_{C-P}=11.6$ Hz) and 128.5 (CH, d, $^3J_{C-P}=11.6$ Hz) (Ar-CH_{meta}), 78.4 (CH, dd, $^3J_{C-P}=5.6$ Hz, $^3J_{C-P}=9.1$ Hz, C1), 42.1 (CH, t, $^2J_{C-P}=^3J_{C-P}=4.1$ Hz, C2), 34.6 (CH_2, d, $^1J_{C-P}=69.9$ Hz, CH_2-P), 33.8 (CH_2, broad s, C5), 32.7 (CH, d, $^1J_{C-P}=74.4$ Hz, C4), 31.1 (CH_2, dd, $^2J_{C-P}=2.3$ Hz, $^3J_{C-P}=13.5$ Hz, C3); ^{31}P NMR 33,8 [CH-$PO(C_6H_5)_2$], 32.3 [$CH_2PO(C_6H_5)_2$]; MS (EI), m/z (%): 500 ($M^{\bullet+}$, 2), 299 [$[M-PO(C_6H_5)_2]^+$, 72], 281 [$[M-PO(C_6H_5)_2-H_2O]^+$, 10], 215 [$[CH_2PO(C_6H_5)_2]^+$, 13], 202 (41), 201 [$[PO(C_6H_5)_2]^+$, 100], 77 (70). Anal. calcd for: $C_{30}H_{30}O_3P_2\cdot 0.5H_2O$: C, 70.72; H, 6.14. Found: C, 70.76; H, 6.10%.

4.1.18. *c*-4-(Dicyclopentylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol 13c. From a solution of **14c** (77 mg, 0.15 mmol) in methanol (6 mL) and $NaOCH_3$ (17.8 mg, 0.33 mmol) and following the procedure described for **13a**, **13c** (68 mg, 94%) was obtained as a brown solid. An analytical sample of **13c** was obtained by crystallization, mp 144.5–145.5°C (ethyl acetate). IR (KBr) 3393 (OH st), 1167, 1120 (P=O st) cm^{-1}; ^{1}H NMR 7.74–7.68 (complex signal, 4H, Ar-H_{ortho}), 7.55–7.50 (complex signal, 2H, Ar-H_{para}), 7.49–7.44 (complex signal, 4H, Ar-H_{meta}), 6.20–6.00 (broad signal, 1H, OH), 3.93 (dt, $J=8.5$ Hz, $J'=6.0$ Hz, 1H, H-1), 2.50–2.40 [complex signal, 2H, 3-H_α, CH_{syn}-P (δ 2.48, ddd, $J=3.5$ Hz, $J'=7.5$ Hz, $J''=15.0$ Hz)], 2.36–2.15 [complex signal, 3H, 4-H, 5-H_β, CH_{anti}P

(δ 2.26, ddd, $J=10.5$ Hz, $J'=14.5$ Hz, $J'=15.0$ Hz)], 2.08–1.94 (complex signal, 3H, cyclopentyl CH, 2-H), 1.88–1.44 (complex signal, 18H, cyclopentyl CH_2, 3-H_β, 5-H_α); ^{13}C NMR 132.4 (C, d, $^1J_{C-P}=100.7$ Hz) and 131.1 (C, d, $^1J_{C-P}=97.2$ Hz) (Ar-C_{ipso}), 132.0 (CH, d, $^4J_{C-P}=4.1$ Hz) and 131.9 (CH, d, $^4J_{C-P}=3.0$ Hz) (Ar-CH_{para}), 130.8 (CH, d, $^2J_{C-P}=9.6$ Hz) and 130.4 (CH, d, $^2J_{C-P}=9.1$ Hz) (Ar-CH_{ortho}), 128.73 (CH, d, $^3J_{C-P}=11.6$ Hz) and 128.68 (CH, d, $^3J_{C-P}=11.6$ Hz) (Ar-CH_{meta}), 78.2 (CH, dd, $^3J_{C-P}=3.3$ Hz, $^3J'_{C-P}=10.8$ Hz, C1), 41.4 (CH, t, $^2J_{C-P}=^3J_{C-P}=3.8$ Hz, C2), 37.0 (CH, d, $^1J_{C-P}=66.8$ Hz) and 36.3 (CH, d, $^1J_{C-P}=66.3$ Hz) (cyclopentyl CH), 35.1 (CH_2, s, C5), 34.7 [CH_2, d, $^1J_{C-P}=69.8$ Hz, CH_2P], 31.8 (CH_2, dd, $^2J_{C-P}=2.6$ Hz, $^3J_{C-P}=14.2$ Hz, C3), 31.7 (CH, d, $^1J_{C-P}=65.3$ Hz, C4), 27.3 (CH_2, d, $^2J_{C-P}=1.1$ Hz), 27.1 (CH_2, d, $^2J_{C-P}=1.1$ Hz), 26.8 (CH_2, d, $^2J_{C-P}=1.5$ Hz) and 26.7 (CH_2, d, $^2J_{C-P}=1.5$ Hz) (cyclopentyl C2 and C5), 26.12 (CH_2, d, $^3J_{C-P}=9.1$ Hz), 26.06 (CH_2, d, $^3J_{C-P}=9.6$ Hz), 25.99 (CH_2, d, $^3J_{C-P}=10.1$ Hz) and 25.96 (CH_2, d, $^3J_{C-P}=9.7$ Hz) (cyclopentyl C3 and C4); ^{31}P NMR 52.3 [$PO(C_5H_9)_2$], 33.1 [$PO(C_6H_5)_2$]; MS (EI), m/z (%): 485 [$(M+H)^+$, 1], 347 [$(M-C_5H_8-C_5H_9)^+$, 7], 299 [[$M-PO(C_5H_9)_2]^+$, 29], 283 [[$M-PO(C_6H_5)_2]^+$, 100], 281 [[$M-PO(C_5H_9)_2-H_2O]^+$, 25], 215 [[$CH_2PO(C_6H_5)_2]^+$, 20], 202 (30), 201 [[$PO(C_6H_5)_2]^+$, 88], 185 [[$PO(C_5H_9)_2]^+$, 17]. Anal. calcd for: $C_{28}H_{38}O_3P_2$: C, 69.41; H, 7.90. Found: C, 69.61; H, 8.12%.

4.1.19. *t*-4-(Diisopropylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol 16a. From a solution of **17a** (430 mg, 0.91 mmol) in methanol (12 mL) and $NaOCH_3$ (108 mg, 2.0 mmol) and following the procedure described for **13a**, **16a** (380 mg, 97%) was obtained as a foamy white solid. An analytical sample of **16a** was obtained by crystallization, mp 170–172°C (ethyl acetate). IR (KBr) 3299 (OH st), 1175, 1150 (P=O st) cm^{-1}; ^{1}H NMR 7.77–7.68 (complex signal, 4H, Ar-H_{ortho}), 7.55–7.43 (complex signal, 6H, Ar-H_{meta}, Ar-H_{para}), 5.74 (d, $J=1.5$ Hz, 1H, OH), 4.09 (pseudo dq, $J=1.5$ Hz, $J'=7.0$ Hz, 1H, 1-H), 2.52 (ddd, $J=3.0$ Hz, $J'=7.0$ Hz, $J''=15.0$ Hz, 1H, CH_{syn}P), 2,48 (tt, $J=9.0$ Hz, $J'=14.0$ Hz, 1H, 5-H_β), 2.42–2.32 (m, 1H, 4-H), 2.34 (ddd, $J=10.5$ Hz, $J'=$ 14.5 Hz, $J''=15.0$ Hz, 1H, CH_{anti}P), 2.09–1.91 [complex signal, 4H, 2 C$\underline{H}(CH_3)_2$, 2-H, 3-H_α], 1.83 (m, 1H, 5-H_α), 1.77 (pseudo q, $J=11.5$ Hz, 1H, 3-H_β), 1.16 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H), 1.15 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H), 1,14 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H) and 1.12 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H) [2 CH($C\underline{H}_3)_2$]; ^{13}C NMR 132.9 (C, d, $^1J_{C-P}=100.4$ Hz) and 131.6 (C, d, $^1J_{C-P}=97.6$ Hz) (Ar-C_{ipso}), 132.0 (CH, d, $^4J_{C-P}=2.7$ Hz) and 131.9 (CH, d, $^4J_{C-P}=2.8$ Hz) (Ar-CH_{para}), 131.0 (CH, d, $^2J_{C-P}=9.1$ Hz) and 130.4 (CH, d, $^2J_{C-P}=9.5$ Hz) (Ar-CH_{ortho}), 128.8 (CH, d, $^3J_{C-P}=11.9$ Hz, Ar-CH_{meta}), 77.6 (CH, dd, $^3J_{C-P}=2.9$ Hz, $^3J_{C-P}=7.5$ Hz, C1), 43.9 (CH, dd, $^2J_{C-P}=3.8$ Hz, $^3J_{C-P}=9.6$ Hz, C2), 34.3 (CH_2, dd, $^2J_{C-P}=3.1$ Hz, $^3J_{C-P}=14.4$ Hz, C3), 33.58 [CH_2, d, $^1J_{C-P}=69.9$ Hz, CH_2P], 33.55 (CH_2, d, $^2J_{C-P}=2.4$ Hz, C5), 31.2 (CH, d, $^1J_{C-P}=63.5$ Hz, C4), 26.2 (CH, d, $^1J_{C-P}=62.6$ Hz) and 26.0 (CH, d, $^1J_{C-P}=62.6$ Hz) [2 C$\underline{H}(CH_3)_2$], 16.75 (CH_3, d, $^2J_{C-P}=2.5$ Hz), 16.73 (CH_3, d, $^2J_{C-P}=2.1$ Hz), 16.6 (CH_3, d, $^2J_{C-P}=2.4$ Hz) and 16.5 (CH_3, d, $^2J_{C-P}=$ 2.2 Hz) [2 CH($C\underline{H}_3)_2$]; ^{31}P NMR 56.7 [$PO(i\text{-}Pr)_2$], 34.9 [$PO(C_6H_5)_2$]; MS (EI), m/z (%): 433 [$(M+H)^+$, 3], 432 ($M^{\bullet+}$, 1), 347 [$(M-C_3H_6-C_3H_7)^+$, 13], 299 [$(M-(i\text{-}Pr)_2PO]^+$, 68], 281 [[$M-H_2O-(i\text{-}Pr)_2PO]^+$, 47], 231 [[$M-PO(C_6H_5)_2]^+$, 95], 217 [[$M-CH_2PO(C_6H_5)_2]^+$, 70], 215 [[$CH_2PO(C_6H_5)_2]^+$, 24], 201 [[$PO(C_6H_5)_2]^+$, 100], 135 [$(i\text{-}Pr)_2POH_2]^+$, 64]. Anal. calcd for $C_{24}H_{34}O_3P_2\cdot H_2O$: C, 63.98; H, 8.06. Found: C, 64.18; H, 7.69%.

4.1.20. *t*-4-(Diphenylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol 16b. From a solution of **17b** (530 mg, 0.98 mmol) in methanol (40 mL) and $NaOCH_3$ (116 mg, 2.15 mmol) and following the procedure described for **13a**, **16b** (480 mg, 98%) was obtained as a foamy brown solid. An analytical sample of **16b** was obtained by crystallization, mp 175–176.5°C (ethyl acetate). IR (KBr) 3422 (OH st), 1188, 1167, 1118 (P=O st) cm^{-1}; ^{1}H NMR 7.73–7.64 (complex signal, 8H, Ar-H_{ortho}), 7.53–7.38 (complex signal, 12H, Ar-H_{para}, Ar-H_{meta}), 6.00–5.20 (broad signal, 1H, OH), 4.10 (dt, $J=8.5$ Hz, $J'=7.5$ Hz, 1H, 1-H), 2.90 (dtt, $J=2.5$ Hz, $J'=8.0$ Hz, $J''=10.5$ Hz, 1H, 4-H), 2.50–2.40 [complex signal, 2H, 5-H_β and CH_{syn}-P (δ 2.48, ddd, $J=2.5$ Hz, $J'=7.0$ Hz, $J''=15.0$ Hz)], 2.30 (dt, $J=11.0$ Hz, $J'=15.0$ Hz, 1H, CH_{anti}-P), 2.11–2.01 (m, 1H, 2-H), 1.85–1.76 (complex signal, 3H, 3-H_α, 3-H_β, 5-H_α); ^{13}C NMR 132.8 (C, d, $^1J_{C-P}=96.6$ Hz), 132.7 (C, d, $^1J_{C-P}=100.2$ Hz), 132.3 (C, d, $^1J_{C-P}=97.7$ Hz) and 131.3 (C, d, $^1J_{C-P}=99.8$ Hz) (Ar-C_{ipso}), 132.0 (CH, d, $^4J_{C-P}=2.7$ Hz), 131.9 (CH, d, $^4J_{C-P}=3.2$ Hz), 131.6 (CH, d, $^4J_{C-P}=2.8$ Hz) and 131.5 (CH, d, $^4J_{C-P}=2.2$ Hz) (Ar-CH_{para}), 131.0 (CH, d, $^2J_{C-P}=9.4$ Hz), 130.8 (CH, d, $^2J_{C-P}=9.4$ Hz), 130.7 (CH, d, $^2J_{C-P}=8.8$ Hz) and 130.3 (CH, d, $^2J_{C-P}=9.4$ Hz) (Ar-CH_{ortho}), 128.75 (CH, d, $^3J_{C-P}=11.5$ Hz), 128.73 (CH, d, $^3J_{C-P}=11.5$ Hz), 128.54 (CH, d, $^3J_{C-P}=10.9$ Hz) and 128.48 (CH, d, $^3J_{C-P}=11.0$ Hz) (Ar-CH_{meta}), 77.7 (CH, dd, $^3J_{C-P}=1.9$ Hz, $^3J_{C-P}=6.3$ Hz, C1), 44.0 (CH, dd, $^2J_{C-P}=3.6$ Hz, $^3J_{C-P}=10.2$ Hz, C2), 34.6 (CH, dd, $^4J_{C-P}=1.0$ Hz, $^1J_{C-P}=77.4$ Hz, C4), 33.7 (CH_2, d, $^1J_{C-P}=69.2$ Hz, CH_2-P), 33.3 (CH_2, d, $^2J_{C-P}=1.9$ Hz, C5), 33.2 (CH_2, dd, $^2J_{C-P}=2.6$ Hz, $^3J_{C-P}=14.6$ Hz, C3); ^{31}P NMR 32.7 [$PO(C_6H_5)_2$], 31.3 [$CH_2PO(C_6H_5)_2$]; MS (EI), m/z (%): 500 ($M^{\bullet+}$, 1), 299 [[$M-PO(C_6H_5)_2]^+$, 60], 281 [[$M-H_2O-PO(C_6H_5)_2]^+$, 14], 217 (23), 215 [[$CH_2PO(C_6H_5)_2]^+$, 19], 203 (43), 202 (45), 201 [[$PO(C_6H_5)_2]^+$, 100]. Anal. calcd for: $C_{30}H_{30}O_3P_2\cdot 0.25H_2O$: C, 71.35; H, 6.09. Found: C, 71.31; H, 6.04%.

4.1.21. *t*-4-(Dicyclopentylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol 16c. To a solution of **17c** (50 mg, 0.095 mmol) in ethanol (10 mL) was added KCN (0.5 mg, 7.7 μmol) and the mixture was heated under reflux for 12 h. The mixture was allowed to cool to room temperature and the solvent was evaporated in vacuo to dryness. The residue was dissolved in H_2O (10 mL) and was extracted with CH_2Cl_2 (3×5 mL). The combined organic extracts were dried (Na_2SO_4), filtered and concentrated in vacuo to give **18c** (38 mg, 83%) as a brown solid. An analytical sample of **16c** was obtained by crystallization, mp 148–149°C (ethyl acetate). IR (KBr) 3292 (OH st), 1180, 1163, 1119 (P=O st) cm^{-1}; ^{1}H NMR 7.76–7.67

(complex signal, 4H, Ar-H_{ortho}), 7.55–7.44 (complex signal, 6H, Ar-H_{meta}, Ar-H_{para}), 5.72 (d, $J=1.0$ Hz, 1H, OH), 4.08 (q, $J=7.0$ Hz, 1H, 1-H), 2.55 (ddd, $J=2.5$ Hz, $J'=6.5$ Hz, $J''=15.2$ Hz, 1H, CH_{syn}-P), 2.44 (tt, $J=9.0$ Hz, $J'=14.0$ Hz, 1H, 5-H_β), 2.36–2.24 [complex signal, 2H, 4-H, CH_{anti}P (δ 2.30, dt, $J=10.5$ Hz, $J'=$ 15.0 Hz)], 2.09–1.94 (complex signal, 4H, cyclopentyl CH, 2-H, 3-H_α), 1.88–1.48 (complex signal, 18H, cyclopentyl CH_2, 3-H_β, 5-H_α); ^{13}C NMR 132.7 (C, d, $^1J_{C-P}=99.9$ Hz) and 131.4 (C, d, $^1J_{C-P}=97.7$ Hz) (Ar-C_{ipso}), 131.9 (CH, d, $^4J_{C-P}=2.8$ Hz) and 131.8 (CH, d, $^4J_{C-P}=2.8$ Hz) (Ar-CH_{para}), 130.9 (CH, d, $^2J_{C-P}=9.9$ Hz) and 130.2 (CH, d, $^2J_{C-P}=9.9$ Hz) (Ar-CH_{ortho}), 128.7 (CH, d, $^3J_{C-P}=11.5$ Hz, Ar-CH_{meta}), 77.6 (CH, dd, $^3J_{C-P}=3.3$ Hz, $^3J_{C-P}=7.7$ Hz, C1), 43.8 (CH, dd, $^2J_{C-P}=3.8$ Hz, $^3J_{C-P}=10.4$ Hz, C2), 37.1 (CH, d, $^1J_{C-P}=66.4$ Hz) and 36.8 (CH, d, $^1J_{C-P}=66.4$ Hz) (cyclopentyl CH), 34.6 (CH_2, dd, $^2J_{C-P}=2.8$ Hz, $^3J_{C-P}=$ 13.7 Hz, C3), 33.8 (CH, d, $^2J_{C-P}=66.4$ Hz, C4), 33.7 (CH_2, d, $^2J_{C-P}=1.1$ Hz, C5), 33.6 (CH_2, d, $^1J_{C-P}=69.7$ Hz, CH_2P), 27.1 (2 CH_2, s), 27.0 (CH_2, s) and 26.9 (CH_2, s) (cyclopentyl C2 and C5), 26.2 (2 CH_2, d, $^3J_{C-P}=9.9$ Hz), 26.1 (CH_2, d, $^3J_{C-P}=9.2$ Hz) and 26.0 (CH_2, d, $^3J_{C-P}=9.3$ Hz) (cyclopentyl C3 and C4); ^{31}P NMR 52.8 [$PO(C_5H_9)_2$], 34.7 [$PO(C_6H_5)_2$]; MS (EI), m/z (%): 485 [$(M+H)^+$, 4], 347 [$(M-C_5H_8-C_5H_9)^+$, 34], 299 [[$M-PO(C_5H_9)_2]^+$, 63], 283 [[$M-PO(C_6H_5)_2]^+$, 100], 281 [[$M-PO(C_6H_5)_2-H_2O]^+$, 32], 269 [[$M-CH_2PO(C_6H_5)_2]^+$, 26], 217 (27), 215 [[$CH_2PO(C_6H_5)_2]^+$, 24], 202 (36), 201 [[$PO(C_6H_5)_2]^+$, 98]. Anal. calcd for: $C_{28}H_{38}O_3P_2$: C, 69.40; H, 7.91. Found: C, 69.44; H, 8.03%.

4.1.22. *trans*-(3,4-Epoxycyclopentyl)diphenylphosphine 15. To a solution of **2b** (200 mg, 0.70 mmol) in anhydrous THF (4 mL), triethoxysilane (0.41 mL, 2.22 mmol) and titanium tetraisopropoxide (20 mg, 0.07 mmol) were added and the mixture was stirred under reflux for 7 h. The solvent was evaporated under reduced pressure. Standard column chromatography of the residue [silica gel (4 g), hexane/ethyl acetate mixtures] gave **15** as a colorless oil (150 mg, 80%). ^{1}H NMR 7.46–7.39 (m, 4H, Ar-H_{ortho}), 7.33–7.29 (complex signal, 6H, Ar-H_{meta}, Ar-H_{para}), 3.49 (d, $J=2.0$ Hz, 2H, 3(4)-H), 2.54 (tq, $J=10.5$ Hz, $J'=7.5$ Hz, 1H, H-1), 2.10 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 2H, 2(5)-H_β), 1.62 (dt, $J=10.5$ Hz, $J'=14.0$ Hz, 2H, 2(5)-H_α); ^{13}C NMR 137.5 (C, d, $^1J_{C-P}=13.2$ Hz, Ar-C_{ipso}), 132.9 (CH, d, $^2J_{C-P}=19.3$ Hz, Ar-CH_{ortho}), 128.8 (CH, s, Ar-CH_{para}), 128.3 (CH, d, $^3J_{C-P}=7.1$ Hz, Ar-CH_{meta}), 57.5 [CH, d, $^3J_{C-P}=12.7$ Hz, C3(4)], 32.5 [CH_2, d, $^2J_{C-P}=20.3$ Hz, C2(5)], 28.7 (CH, d, $^1J_{C-P}=8.1$ Hz, C1); ^{31}P NMR −7.0.

4.1.23. *O*-[*c*-4-(Diphenylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-cyclopentyl] imidazole-1-carbothioate 18. To a solution of alcohol **13b** (200 mg, 0.40 mmol) in anhydrous toluene (15 mL) was added thiocarbonyldiimidazole (120 mg, 90% content, 0.61 mmol) and the mixture was heated under reflux for 1 h. The mixture was allowed to cool to room temperature and the separated solid (a mixture of **18** and imidazole) was collected by filtration. Elimination of imidazole by sublimation (60°C/1 Torr) gave pure **18** (161 mg, 65%) as a white solid. An analytical sample of **18** was obtained by crystallization (ethyl acetate), mp 192–193°C. IR (KBr) 1182, 1120 (P=O st) cm^{-1}; ^{1}H NMR 8.23 (s, 1H, imidazole 2-H), 7.71–7.66 (complex signal, 8H, Ar-H_{ortho}), 7.62 (broad s, 1H, imidazole 5-H), 7.52–7.38 (complex signal, 12H, Ar-H_{meta}, Ar-H_{para}), 6.98 (broad s, 1H, imidazole 4-H), 5.55 (q, $J=5.5$ Hz, 1H, 1-H), 3.06 (dq, $J=3.5$ Hz, $J'=9.0$ Hz, 1H, 4-H), 2.83–2.74 (m, 1H, 2-H), 2.53–2.44 (complex signal, 2H, 5-H_β, CH_{syn}-P), 2.43–2.33 (m, 1H, 3-H_α), 2.25 (ddd, $J=10.0$ Hz, $J'=13.0$ Hz, $J''=15.0$ Hz, 1H, CH_{anti}-P), 2.14 (dddd, $J=5.5$ Hz, $J'=8.5$ Hz, $J''=14.0$ Hz, $J'''=18.0$ Hz, 1H, 5-H_α), 2.06–1.98 (m, 1H, 3-H_β); ^{13}C NMR 183.6 (C, s, CS), 137.2 (CH, s, imidazole C2), 133.1 (C, d, $^1J_{C-P}=96.6$ Hz), 132.2 (C, d, $^1J_{C-P}=97.6$ Hz), 131.8 (C, d, $^1J_{C-P}=96.6$ Hz) and 131.7 (C, $^1J_{C-P}=97.7$ Hz) (Ar-C_{ipso}), 131.9–131.7 (CH, complex signal, Ar-CH_{para}), 130.9–130.2 (CH, complex signal, Ar-CH_{ortho}, imidazole C4), 128.8–128.5 (CH, complex signal, Ar-CH_{meta}), 117.8 (CH, s, imidazole C5), 88.6 (CH, dd, $^3J_{C-P}=7.7$ Hz, $^3J_{C-P}=12.6$ Hz, C1), 39.6 (CH, broad s, C2), 33.3 (CH, d, $^1J_{C-P}=74.7$ Hz, C4), 31.7 (CH_2, d, $^1J_{C-P}=70.9$ Hz, CH_2-P), 30.0 (CH_2, s, C5), 29.4 (CH_2, broad s, C3); ^{31}P NMR 32.2 [Cy−$PO(C_6H_5)_2$], 27.9 [$CH_2PO(C_6H_5)_2$]; MS (EI), m/e (%): 483 [[$M-(C_3H_3N_2)$-$C(S)O]^+$, 3], 482 (3), 281 [[$M-(C_3H_3N_2)C(S)O-PO(C_6H_5)_2]^+$, 66], 202 (34), 201 [[$PO(C_6H_5)_2]^+$, 100]. Anal. calcd for $C_{34}H_{32}N_2O_3P_2S\cdot0.5H_2O$: C, 65.90; H, 5.37. Found: C, 65.91; H, 5.15%.

4.1.24. *trans*-1-(Diphenylphosphinoyl)-3-[diphenylphosphinoyl)methyl]cyclopentane 19. To a solution of **18** (155 mg, 0.25 mmol) in anhydrous toluene (70 mL) was added dropwise (n-Bu)$_3$SnH (0.35 mL, 1.25 mmol) and azobis(isobutyronitrile) (AIBN) (8.38 mg, 0.05 mmol) and the mixture was heated under reflux for 4 h. The mixture was allowed to cool to room temperature and the solvent was removed under vacuum to give a solid residue (860 mg), which was submitted to flash column chromatography [silica gel (8 g), ethyl acetate/methanol mixtures] to give pure **19** (68 mg, 56%), as a white solid, on elution with a mixture ethyl acetate/methanol in the ratio of 90:10. An analytical sample was obtained by crystallization, mp 55–56°C (ethyl acetate). IR (KBr) 1176, 1119 (P=O st) cm^{-1}; ^{1}H NMR 7.71–7.65 (complex signal, 8H, Ar-H_{ortho}), 7.49–7.37 (complex signal, 12H, Ar-H_{meta}, Ar-H_{para}), 2.88–2.79 (m, 1H, 1-H), 2.35–2.25 (complex signal, 3H, CH_2-P, 3-H), 2.24–2.14 (m, 1H, 2-H_α), 2.03–1.95 (m, 1H, 4-H_β or 4-H_α), 1.90–1.77 (complex signal, 2H, 5-H_α, 5-H_β), 1.63 (ddt, $J=6.5$ Hz, $J'=13.5$ Hz, $J''=10.5$ Hz, 1H, 2-H_β), 1.42–1.34 (m, 1H, 4-H_α or 4-H_β); ^{13}C NMR 133.27 (C, d, $^1J_{C-P}=98.2$ Hz), 132.99 (C, d, $^1J_{C-P}=97.7$ Hz), 132.86 (C, d, $^1J_{C-P}=96.1$ Hz) and 132.76 (C, d, $^1J_{C-P}=96.7$ Hz) (Ar-C_{ipso}), 131.5 (CH, broad signal) and 131.4 (CH, d, $^4J_{C-P}=2.2$ Hz) (2+2 Ar-CH_{para}), 130.86 (CH, d, $^2J_{C-P}=8.7$ Hz), 130.79 (CH, d, $^2J_{C-P}=8.8$ Hz), 130.55 (CH, d, $^2J_{C-P}=8.7$ Hz) and 130.51 (CH, d, $^2J_{C-P}=9.3$ Hz) (Ar-CH_{ortho}), 128.54 (CH, d, $^3J_{C-P}=11.0$ Hz), 128.52 (CH, d, $^3J_{C-P}=9.8$ Hz), 128.41 (CH, d, $^3J_{C-P}=10.9$ Hz) and 128.38 (CH, d, $^3J_{C-P}=10.9$ Hz) (Ar-CH_{meta}), 35.8 (CH, d, $^1J_{C-P}=84.5$ Hz, C1), 35.4 (CH_2, s, C2), 35.2 (CH_2, d, $^1J_{C-P}=71.4$ Hz, CH_2-P), 34.6 (CH, dd, $^2J_{C-P}=3.8$ Hz, $^3J_{C-P}=6.0$

Hz, C3), 33.6 (CH_2, broad d, $^3J_{C-P}=8.7$ Hz, C4), 26.0 (CH_2, d, $^2J_{C-P}=1.7$ Hz, C5); ^{31}P NMR 33.3 [Cy-$PO(C_6H_5)_2$], 28.6 [$CH_2PO(C_6H_5)_2$]; MS (EI), *m/e* (%): 484 ($M^{\bullet+}$, 5), 284 (20), 283 [[M−$PO(C_6H_5)_2$]$^+$, 100], 215 [[$CH_2PO(C_6H_5)_2$]$^+$, 19], 202 (24), 201 [[$PO(C_6H_5)_2$]$^+$, 83]; Anal. calcd for $C_{30}H_{30}O_2P_2\cdot1.5H_2O$: C, 70.44; H, 6.51. Found: C, 70.24; H, 6.38%.

4.1.25. *O*-[*t*-4-(Diphenylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-cyclopentyl imidazole-1-carbothioate 20. To a solution of alcohol **16b** (50 mg, 0.10 mmol) in anhydrous CH_2Cl_2 (8 mL) was added thiocarbonyldiimidazole (30 mg, 90% content, 0.15 mmol) and the mixture was heated under reflux for 4 h. The solvent was evaporated under reduced pressure to give a yellow residue (77 mg) mixture of **20** and imidazole. An analytical sample of **20** was obtained by crystallization, mp 170.5–171°C (ethyl acetate/methanol, 10:1). IR (KBr) 1180 (P=O st) cm^{-1}; ^{1}H NMR 8.15 (s, 1H, imidazole 2-H), 7.73–7.60 (complex signal, 8H, Ar-H_{ortho}), 7.52–7.34 (complex signal, 13H, Ar-H_{meta}, Ar-H_{para}, imidazole 5-H), 6.99 (broad s, 1H, imidazole 4-H), 5.55 (broad pseudo dt, $J=3.5$ Hz, $J'=6.5$ Hz, 1H, 1-H), 2.97–2.87 (complex signal, 2H, 2-H, 4-H), 2.65 (dddd, $J=7.5$ Hz, $J'=9.5$ Hz, $J''=15.0$ Hz, $J'''=17.0$ Hz, 1H, 5-H_β), 2.60–2.50 [complex signal, 2H, CH_2P], 2.09–2.02 (m, 1H, 3-H_α), 1.92–1.85 (m, 1H, 5-H_α), 1.80–1.70 (m, 1H, 3-H_β); ^{13}C NMR 182.8 (C, s, CS), 136.7 (CH, s, imidazole C2), 133.1 (C, d, $^1J_{C-P}=99.2$ Hz), 133.1 (C, higher δ signal of a d), 132.1 (C, d, $^1J_{C-P}=98.2$ Hz) and 131.9 (C, d, $^1J_{C-P}=98.7$ Hz) (Ar-C_{ipso}), 131.9–131.6 (CH, complex signal, Ar-CH_{para}), 130.8–130.4 (CH, complex signal, Ar-CH_{ortho}, imidazole C4), 128.9–128.5 (CH, complex signal, Ar-CH_{meta}), 117.9 (CH, s, imidazole C5), 89.5 (CH, dd, $^3J_{C-P}=9.1$ Hz, $^3J'_{C-P}=11.1$ Hz, C1), 39.7 (CH, dd, $^2J_{C-P}=3.5$ Hz, $^3J_{C-P}=9.1$ Hz, C2), 35.4 (CH, d, $^1J_{C-P}=75.4$ Hz, C4), 32.5 [CH_2, d, $^1J_{C-P}=70.9$ Hz, CH_2P], 31.5 (CH_2, broad d, $^3J_{C-P}=5.5$ Hz, C3), 30.9 (CH_2, s, C5); ^{31}P NMR 30.5 [Cy-$PO(C_6H_5)_2$], 27.4 [$CH_2PO(C_6H_5)_2$]; MS (EI), *m/e* (%): 482 [[(M−$(C_3H_3N_2)C(S)OH)$]$^{\bullet+}$, 2], 281 [[M−$(C_3H_3N_2)C(S)OH$)−$PO(C_6H_5)_2$]$^+$, 61], 202 (26), 201 [[$PO(C_6H_5)_2$]$^+$, 100], 77 (97). Anal. calcd for $C_{34}H_{32}N_2O_3P_2S\cdot0.75H_2O$: C, 65.43; H, 5.41. Found: C, 65.41; H, 5.25%.

4.1.26. *cis*-1-(Diphenylphosphinoyl)-3-(diphenylphosphinoylmethyl)cyclopentane 21. To a solution of **20** (61 mg, 0.10 mmol) in anhydrous benzene (15 mL) was added dropwise (n-Bu)$_3$SnH (0.14 mL, 0.5 mmol) and AIBN (3.3 mg, 0.02 mmol) and the mixture was heated under reflux for 6 h. The mixture was allowed to cool to room temperature and the solvent was removed under vacuum. The residue was dissolved in acetonitrile (8 mL), the solution was washed with hexane (3×8 mL) and the acetonitrile evaporated under reduced pressure to give impure **21** as a brown solid (64 mg). An analytical sample of **21** was obtained by crystallization, mp 172–173°C (ethyl acetate). IR (KBr) 1177, 1120 (P=O st) cm^{-1}; ^{1}H NMR 7.73–7.65 (complex signal, 6H) and 7.61–7.57 (complex signal, 2H) (Ar-H_{ortho}), 7.49–7.33 (complex signal, 12H, Ar-H_{para}, Ar-H_{meta}), 2.74–2.65 (m, 1H, 1-H), 2.43–2.38 (complex signal, 3H, CH_2P, 3-H), 2.05–1.94 (m, 1H, 5-H_α), 1.84–1.74 (complex signal, 2H, 2-H_β, 4-H_β), 1.74–1.64 (m, 1H, 5-H_β), 1.50 (ddt, $J=12.5$ Hz, $J'=17.0$ Hz, $J''=10.0$ Hz, 1H, 2-H_α), 1.36 (dq, $J=9.5$ Hz, $J'=12.5$ Hz, 1H, 4-H_α); ^{13}C NMR 133.4 (C, d, $^1J_{C-P}=97.7$ Hz), 133.2 (C, d, $^1J_{C-P}=97.2$ Hz), 132.9 (C, d, $^1J_{C-P}=96.1$ Hz) and 132.8 (C, d, $^1J_{C-P}=96.6$ Hz) (Ar-C_{ipso}), 131.6 (CH, d, $^4J_{C-P}=2.8$ Hz), 131.5 (2 CH, d, $^4J_{C-P}=2.8$ Hz) and 131.3 (CH, d, $^4J_{C-P}=2.8$ Hz) (Ar-CH_{para}), 130.73 (CH, d, $^2J_{C-P}=8.8$ Hz), 130.64 (CH, d, $^2J_{C-P}=9.3$ Hz), 130.55 (CH, d, $^2J_{C-P}=9.3$ Hz) and 130.50 (CH, d, $^2J_{C-P}=9.3$ Hz) (Ar-CH_{ortho}), 128.52 (CH, d, $^3J_{CP}=11.5$ Hz), 128.49 (CH, d, $^3J_{C-P}=11.5$ Hz), 128.42 (CH, d, $^3J_{C-P}=11.5$ Hz) and 128.37 (CH, d, $^3J_{C-P}=10.9$ Hz) (Ar-CH_{meta}), 36.4 (CH, d, $^1J_{C-P}=75.2$ Hz, C1), 35.0 (CH, dd, $^2J_{C-P}=4.4$ Hz, $^3J_{C-P}=10.5$ Hz, C3), 34.5 (CH_2, d, $^1J_{C-P}=70.8$ Hz, CH_2P), 34.4 (CH_2, broad s, C4), 34.3 (CH_2, dd, $^2J_{C-P}$ and $^3J_{CP}=1.5$ and 2.5 Hz, C2), 24.9 (CH_2, s, C5); ^{31}P NMR δ: 32.6 [Cy-$PO(C_6H_5)_2$], 28.4 [$CH_2PO(C_6H_5)_2$]; MS (EI), *m/z* (%): 484 ($M^{\bullet+}$, 5), 283 [[M−$PO(C_6H_5)_2$]$^+$, 100], 269 [[M−$CH_2PO(C_6H_5)_2$]$^+$, 15], 215 [[$CH_2PO(C_6H_5)_2$]$^+$, 12], 201 [[$PO(C_6H_5)_2$]$^+$, 44]. Anal. calcd for $C_{30}H_{30}O_2P\cdot H_2O$: C, 71.70; H, 6.42. Found: C, 71.72; H, 6.55%.

4.1.27. (1*S*,2*S*,4*R*)- and (1*R*,2*R*,4*S*)-4-(Diisopropylphosphinoyl)-2-[(diphenylphosphinoyl)methyl]cyclopentyl *N*-[(*S*)-α-phenylethyl]carbamate 22 and 23

4.1.27.1. Mixture of carbamates 22 and 23. To a solution of **16a** (360 mg, 0.83 mmol) in anhydrous benzene (15 mL) was added dropwise anhydrous Et_3N (0.145 mL, 1.04 mmol) and (–)-(*S*)-α-phenylethylisocyanate (96% e.e., 0.147 mL, 1.04 mmol) and the mixture was heated under reflux for 6 h. The mixture was allowed to cool to room temperature, more (–)-(*S*)-α-phenylethylisocyanate (0.147 mL, 1.04 mmol) was added dropwise and the mixture was heated under reflux for 18 h. The mixture was cooled to room temperature and was concentrated in vacuo to give a solid residue (642 mg), which was submitted to flash column chromatography [silica gel (30 g), ethyl acetate/methanol mixtures] to give a mixture of **22** and **23** (420 mg, 87%) on elution with a mixture of ethyl acetate/methanol in the ratio of 90:10. Repeated crystallization of this mixture from ethyl acetate/methanol in the approximate ratio of 15:1) allowed the separation of both diastereomers. The different fractions were analyzed by Chiral HPLC [conditions A: **23**: $t_r=34.9$ min and **22**: $t_r=42.3$ min, $k'_1=4.0$, $k'_2=5.0$, $\alpha=1.43$ and $R_s=0.9$] and were conveniently combined, finally obtaining: fraction **I** (67 mg, pure **23**), fraction **II** (130 mg, pure **22**) and fraction **III** (209 mg, mixture of **23** and **22** enriched in **23**).

4.1.27.2. Analytical and spectroscopic data for 22. Mp 210–212°C (ethyl acetate/methanol in a ratio close to 6:1). IR (KBr) 3425, 3223 (NH st and OH st, H_2O), 1709 (C=O st), 1183, 1148 (P=O st) cm^{-1}; ^{1}H NMR 7.82–7.64 (complex signal, 4H, Ar-H_{ortho}), 7.52–7.40 (complex signal, 6H, Ar-H_{meta}, Ar-H_{para}), 7.36–7.14 (complex signal, 5H, benzyl Ar-H), 4.99 (broad signal, 1H, NH), 4.83 (broad signal, 1H, 1-H), 4.78 (broad signal, 1H, α-H), 2.74 (pseudo t, $J=13.0$ Hz, 1H, $CH_{syn}P$), 2.51 (broad signal, 1H, 2-H), 2.44–2.29 [com-

plex signal, 2H, 5-H_β, $CH_{anti}P$ (δ 2.33 dt, $J=7.0$ Hz, $J'=13.5$ Hz)], 2.24 (broad signal, 1H, 4-H), 2.00–1.80 [complex signal, 3H, 2 C$\underline{H}(CH_3)_2$, 3-H_α], 1.79 (broad s, 3H, 5-H_α, H_2O), 1.54–1.30 [complex signal, 4H, 3-H_β, α-CH_3 (δ 1.45, d, $J=5.5$ Hz)], 1.12 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H), 1.11 (dd, $J=7.5$ Hz, $J'=14.5$ Hz, 3H), 1.05 (dd, $J=7.0$ Hz, $J'=14.5$ Hz, 3H) and 0.98 (dd, $J=7.2$ Hz, $J'=14.2$ Hz, 3H) [2 $CH(C\underline{H}_3)_2$]; ^{13}C NMR 155.0 (C, s, O$\underline{C}$ONH), 143.3 (C, s, Ar-C_{ipso} benzyl), 133.3 (C, d, $^1J_{C-P}=95.8$ Hz) and 133.2 (C, d, $^1J_{C-P}=97.7$ Hz) (Ar-C_{ipso}), 131.6 (CH, $^4J_{C-P}=3.0$ Hz) and 131.5 (CH, $^4J_{C-P}=2.3$ Hz) (Ar-CH_{para}), 130.8 (CH, d, $^2J_{C-P}=9.6$ Hz) and 130.6 (CH, d, $^2J_{C-P}=9.1$ Hz) (Ar-CH_{ortho}), 128.56 (CH, d, $^3J_{C-P}=11.6$ Hz, Ar-CH_{meta}), 128.55 (CH, s, Ar-CH_{meta} benzyl), 128.51 (CH, d, $^3J_{C-P}=11.6$ Hz, Ar-CH_{meta}), 127.2 (CH, broad s, Ar-CH_{para} benzyl), 125.8 (CH, broad s, Ar-CH_{ortho} benzyl), 81.6 (CH, broad signal, C1), 50.6 (CH, s, Cα), 40.4 (CH, dd, $^2J_{C-P}=3.0$ Hz, $^3J_{C-P}=8.2$ Hz, C2), 32.7 (CH_2, d, $^1J_{C-P}\sim75$ Hz, CH_2P), 32.2 (CH_2, broad s, C5), 32.0 (CH, d, $^1J_{C-P}=63.3$ Hz, C4), 31.8 (CH_2, broad s, C3), 26.3 (CH, d, $^1J_{C-P}=62.7$ Hz) and 26.0 (CH, d, $^1J_{C-P}=62.8$ Hz) [2 C$\underline{H}(CH_3)_2$], 22.5 (CH_3, broad s, α-CH_3), 16.8 (CH_3, d, $^2J_{C-P}=2.0$ Hz), 16.7 (CH_3, d, $^2J_{C-P}=2.0$ Hz), 16.67 (CH_3, d, $^2J_{C-P}=2.6$ Hz) and 16.58 (CH_3, d, $^2J_{C-P}=2.5$ Hz) [2 $CH(\underline{C}H_3)_2$]; ^{31}P NMR 54.1 [$PO(i\text{-}Pr)_2$], 28.3 [$PO(C_6H_5)_2$]; MS (EI), m/z (%): 579 ($M^{\bullet+}$, 0,4), 415 [$(M-C_8H_9NHCOO)^+$, 4], 299 [[$M-C_8H_9NCO-(i\text{-}Pr)_2PO]^+$, 17], 281 [$M-C_8H_9NHCOOH-(i\text{-}Pr)_2PO]^+$, 90], 231 [[$M-C_8H_9NCO-PO(C_6H_5)_2]^+$, 14], 217 [[$M-C_8H_9NCO-CH_2PO(C_6H_5)_2]^+$, 19], 201 [$[PO(C_6H_5)_2]^+$, 100], 147 [$(C_8H_9NCO)^{\bullet+}$, 29], 132 [$(C_6H_5CHNCO)^+$, 62]. Anal. calcd for $C_{33}H_{43}NO_4P_2\cdot H_2O$: C, 66.31; H, 7.59; N, 2.34. Found: C, 66.19; H, 7.33; N, 2.40%. $[\alpha]_D^{25}=+4.5$ ($CHCl_3$, $c=1.1$).

4.1.27.3. Analytical and spectroscopic data for 23. Mp 237–240°C (ethyl acetate/methanol in a ratio close to 6:1). IR (KBr) 3228 (NH st), 1710 (C=O st), 1179, 1148 (P=O st) cm^{-1}; ^1H NMR 7.82–7.64 (complex signal, 4H, Ar-H_{ortho}), 7.50–7.38 (complex signal, 6H, Ar-H_{meta}, Ar-H_{para}), 7.38–7.10 (complex signal, 5H, benzyl Ar-H), 4.93 (broad signal, 1H, NH), 4.86–4.74 (complex signal) and 4.56–4.44 (broad signal) (2H, 1-H, α-H), 2.65 (pseudo t, $J=13.0$ Hz, 1H, $CH_{syn}P$), 2.6–2.2 (complex signal, 4H, 2-H, 4-H, 5-H_α, $CH_{anti}P$), 2.2–1.7 [complex signal, 4H, 5-H_β, 2 C$\underline{H}(CH_3)_2$ and 3-H_α], 1.6–1.3 (complex signal, 4H, 3-H_β, α-CH_3), 1.2–0.9 [complex signal, 12H, 2 $CH(C\underline{H}_3)_2$]; ^{13}C NMR 155.0 (C, s, OCONH), 143.3 (C, broad s, benzyl Ar-C_{ipso}), 133.3 (C, d, $^1J_{C-P}=96.7$ Hz) and 129.9 (C, d, $^1J_{C-P}=96.7$ Hz) (Ar-C_{ipso}), 131.62 (CH, $^4J_{C-P}=3.5$ Hz) and 131.58 (CH, $^4J_{C-P}=3.1$ Hz) (Ar-CH_{para}), 130.8 (CH, d, $^2J_{C-P}=10.1$ Hz) and 130.6 (CH, d, $^2J_{C-P}=9.1$ Hz) (Ar-CH_{ortho}), 128.6 (CH, broad s, benzyl Ar-CH_{meta}), 128.58 (CH, d, $^3J_{C-P}=11.7$ Hz) and 128.53 (CH, d, $^3J_{C-P}=11.7$ Hz) (Ar-CH_{meta}), 127.3 (CH, broad s, benzyl Ar-CH_{para}), 125.9 (CH, broad s, benzyl Ar-CH_{ortho}), 81.6 (CH, broad signal, C1), 50.7 (CH, s, Cα), 40.5 (CH, broad m, C2), 33.1 (CH_2, d, $^1J_{C-P}\approx75$ Hz, CH_2P), 32.1 (CH_2, broad s, C5), 31.9 (CH, broad d, $^1J_{C-P}=63.3$ Hz, C4), 31.7 (CH_2, broad s, C3), 26.3 (CH, d, $^1J_{C-P}=62.7$ Hz) and 26.0 (CH, d, $^1J_{C-P}=62.7$ Hz) [2 C$\underline{H}(CH_3)_2$], 22.5 (CH_3, broad s, α-CH_3), 16,81 (CH_3, d, $^2J_{C-P}=2.5$ Hz), 16.75 (CH_3, d, $^2J_{C-P}=2.5$ Hz), 16.6 (CH_3, d, $^2J_{C-P}=2.5$ Hz) and 16.5 (CH_3, d, $^2J_{C-P}=2.5$ Hz) [2 $CH(\underline{C}H_3)_2$]; ^{31}P NMR 54.9 and 54.2 [$PO(i\text{-}Pr)_2$, 2 rotamers], 28.4 [$PO(C_6H_5)_2$]; MS (EI), m/z (%): 579 ($M^{\bullet+}$, 0.1), 446 [$(M-(i\text{-}Pr)_2PO]^+$, 4], 299 [[$M-C_8H_9NCO-(i\text{-}Pr)_2PO]^+$, 16], 281 [$M-C_8H_9NHCOOH-(i\text{-}Pr)_2PO]^+$, 88], 231 [[$M-C_8H_9NCO-PO(C_6H_5)_2]^+$, 14], 217 [[$M-C_8H_9NCO-CH_2PO(C_6H_5)_2]^+$, 18], 215 [$[CH_2PO(C_6H_5)_2]^+$, 11], 201 [$[PO(C_6H_5)_2]^+$, 100], 147 [$(C_8H_9NCO)^{\bullet+}$, 34], 132 [$(C_6H_5CHNCO)^+$, 85). Anal. calcd for $C_{33}H_{43}NO_4P_2$: C, 68.38; H, 7.48; N, 2.42. Found: C, 68.20; H, 7.62; N, 2.41%. $[\alpha]_D^{25}=-52.0$ ($CHCl_3$, $c=0.9$).

4.1.28. X-Ray crystal structure determinations of 13b, 17a, 21, 23 (Table 2)

4.1.28.1. Crystal data for 13b·AcOEt. A prismatic crystal was selected and mounted on a MAR345 diffractometer with an image plate detector. Unit-cell parameters were determined from automatic centering of 9124 reflections ($12<\theta<21°$) and refined by least-squares method. Intensities were collected with graphite-monochromatized Mo-Kα radiation, using $\omega/2\theta$ scan-technique. Reflections were measured in the range $1.97\leq\theta\leq28.87°$ and were assumed as observed applying the condition $I>2\sigma(I)$. Lorentz polarization but no absorption corrections were made. The structure was solved by direct methods, using the SHELXS computer program[26] and refined by full-matrix least-squares method with the SHELX-97 computer program,[27] (very negative intensities were not assumed). The function minimized was $\Sigma w\left||F_o|^2-|F_c|^2\right|^2$, where $w=[\sigma^2(I)+(0.1177P)^2]^{-1}$, and $P=(|F_o|^2+2|F_c|^2)/3$, f, f' and f'' were taken from the literature.[28] Hydrogen atoms were located from a difference synthesis with the exception to those linked to ethyl acetate. Hydrogen atoms linked to carbon atoms were refined using a riding model and an isotropic temperature factor equal to 1.2 times the equivalent isotropic temperature factor of the atom linked to hydrogen. The ethyl acetate molecules are disordered. These were refined with all bond angle and length constrained and a global isotropic temperature factor for each molecule. Goodness of fit = 0.903 for all observed reflections.

4.1.28.2. Crystal data for 17a. A prismatic crystal was selected and mounted on an Enraf–Nonius CAD4 four-circle diffractometer. Unit-cell parameters were determined from automatic centering of 25 reflections ($12<\theta<21°$) and refined by least-squares method. Intensities were collected with graphite-monochromatized Mo-Kα radiation, using $\omega/2\theta$ scan-technique. 6164 reflections were measured in the range $2.00\leq\theta\leq29.96°$, 6112 of which were non-equivalent by symmetry [R_{int}(on I) = 0.007] and 5472 reflections were assumed as observed applying the condition $I>2\sigma(I)$. Three reflections were measured every 2 h as orientation and intensity control, significant intensity decay was not observed. Lorentz polarization but no absorption corrections were made. The structure was solved by direct methods, using the SHELXS computer program[26] and refined by full-matrix least-squares method with the SHELX-93 computer program,[29] using 6062 reflections

(very negative intensities were not assumed). The function minimized was $\Sigma w\left||F_o|^2-|F_c|^2\right|^2$, where $w=[\sigma^2(I)+(0.0634P)^2+0.1524P]^{-1}$ and $P=(|F_o|^2+2|iF_c|^2)/3$, f, f' and f'' were taken from the literature.[28] The extinction coefficient was 0.037(3). All H atoms were located from a difference synthesis and refined, with an overall isotropic temperature factor. Goodness of fit = 1.069 for all observed reflections. Max. shift/esd = 0.00, mean shift/esd = 0.00.

4.1.28.3. Crystal data for 21 monohydrate. A prismatic crystal was selected and mounted on a MAR345 diffractometer with an image plate detector. Unit-cell parameters were determined from automatic centering of 6833 reflections ($3<\theta<31°$) and refined by least-squares method. Intensities were collected with graphite-monochromatized Mo-Kα radiation. 9952 reflections were measured in the range $2.41\leq\theta\leq31.65°$, 3758 of which were non-equivalent by symmetry [R_{int}(on I) = 0.0185]. 2453 reflections were assumed as observed applying the condition $I>2\sigma(I)$. Lorentz polarization but no absorption corrections were made. The structure was solved by direct methods, using the SHELXS computer program[26] and refined by full-matrix least-squares method with the SHELX-97 computer program,[27] using 3758 reflections (very negative intensities were not assumed). The function minimized was $\Sigma w\left||F_o|^2-|F_c|^2\right|^2$, where $w=[\sigma^2(I)+(0.1184P)^2+0.0133P]^{-1}$ and $P=(|F_o|^2+2|F_c|^2)/3$, f, f' and f'' were taken from the literature.[28] All H atoms were computed and refined, using a riding model, with an isotropic temperature factor equal to 1.2 times the equivalent temperature factor of the atom to which are linked. Goodness of fit = 1.115 for all observed reflections. Max. shift/esd = 0.00, mean shift/esd = 0.00.

4.1.28.4. Crystal data for 23. A prismatic crystal was selected and mounted on a Enraf–Nonius CAD4 four-circle diffractometer. Unit-cell parameters were determined from automatic centering of 25 reflections ($12<\theta<21°$) and refined by least-squares method. Intensities were collected with graphite-monochromatized Mo-Kα radiation. 3123 reflections were measured in the range $2.22\leq\theta\leq29.97°$. 2334 reflections were assumed as observed applying the condition $I>2\sigma(I)$. Three reflections were measured every 2 h as orientation and intensity control, significant intensity decay was not observed. Lorentz polarization but no absorption corrections were made. The structure was solved by direct methods, using the SHELXS computer program[26] and refined by full-matrix least-squares method with the SHELX-97 computer program,[27] using 3123 reflections (very negative intensities were not assumed). The function minimized was $\Sigma w\left||F_o|^2-|F_c|^2\right|^2$, where $w=[\sigma^2(I)+(0.0650P)^2]^{-1}$, and $P=(|F_o|^2+2|F_c|^2)/3$, f, f' and f'' were taken from the literature.[28] The chirality of the structure was defined from the Flack coefficient, which is equal to 0.04 (12) for the given results.[30] The extinction coefficient was 0.037(3). Four hydrogen atoms were located from a difference synthesis and refined with an overall isotropic temperature factor and 39 hydrogen atoms were computed and refined with an overall

Table 2. Experimental data for the X-ray crystal-structure determination of compounds **13b**, **17a**, **21** and **23**[25]

Compound	**13b**·AcOEt	**17a**	**21**·H_2O	**23**
Molecular formula	$C_{34}H_{38}O_5P_2$	$C_{26}H_{36}O_4P_2$	$C_{30}H_{32}O_3P_2$	$C_{33}H_{43}NO_4P_2$
Molecular mass	588.58	474.49	502.50	579.62
Crystal system	Monoclinic	Triclinic	Monoclinic	Monoclinic
Space group	$C2/c$	$P\bar{1}$	$P21/c$	$P21$
Cell parameters				
a (Å)	33.42000(10)	10.515(2)	9.4930(10)	8.625(3)
b (Å)	20.31000(10)	10.646(11)	14.2010(10)	17.385(10)
c (Å)	25.50700(10)	12.286(4)	11.0620(10)	11.027(5)
α (°)	90	89.86(5)	90	90
β (°)	130.7810(10)	99.27(2)	117.15	101.19(6)
γ (°)	90	101.51(3)	90	90
V (Å^3)	13109.70(9)	1329(2)	1327.0(2)	1622.0(13)
Z	16	2	2	2
F(000)	4992	508	532	620
D_{calcd} (Mg m^{-3})	1.193	1.185	1.258	1.187
Size of crystal (mm)	0.1 × 0.1 × 0.2	0.1 × 0.1 × 0.2	0.1 × 0.1 × 0.2	0.1 × 0.1 × 0.2
Measured reflections	10042	6164	9952	3123
Independent reflections	10042	6112	3758	3123
Observed reflections	5820	5472	2453	2334
μ(Mo-Kα) (mm^{-1})[a]	0.171	0.191	0.193	0.170
R	0.052	0.043	0.046	0.042
Rw	0.150	0.106	0.181	0.101
$\Delta\rho_{max}$[b] (e Å^{-3})	0.535	0.302	0.277	0.318
$\Delta\rho_{min}$[c] (e Å^{-3})	−0.291	−0.311	−0.314	−0.152
Refined parameters	713	434	184	415
Max. shift/e.s.d.	0.00	0.00	0.00	0.00

[a] μ(Mo-Kα) linear absorption coefficient. Radiation Mo-Kα (λ = 0.71069 Å).
[b] Maximun peaks in final difference synthesis.
[c] Minimum peaks in final difference synthesis.

isotropic temperature factor using a riding model. Goodness of fit = 0.947 for all observed reflections. Max. shift/esd = 0.00, mean shift/esd = 0.00.

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