Pergamon

Tetrahedron 58 (2002) 3473–3484

TETRAHEDRON

Straightforward regio- and stereo-selective synthesis of *t*-2-[(diphenylphosphinoyl)methyl]-*c*-3-(disubstitutedphosphinoyl)-*r*-1-cyclopentanols

Pelayo Camps,[a,*] Gisela Colet,[a] Mercè Font-Bardia,[b] Victoria Muñoz-Torrero,[a] Xavier Solans[b] and Santiago Vázquez[a]

[a]*Laboratori de Química Farmacèutica, Facultat de Farmàcia, Universitat de Barcelona, Av. Diagonal 643, E-08028 Barcelona, Spain*
[b]*Departament de Cristallografia i Dipòsits Minerals, Facultat de Geologia, Universitat de Barcelona, Av. Martí i Franqués, E-08028 Barcelona, Spain*

Received 21 January 2002; revised 28 February 2002; accepted 15 March 2002

Abstract—A 3-step, regio- and stereo-selective, high-yielding synthesis of *t*-2-[(diphenylphosphinoyl)methyl]-*c*-3-(disubstitutedphosphinoyl)-*r*-1-cyclopentanols (**8a–d**) is described. Reaction of epoxides **2a–d** and/or **5a–d** with the lithium derivative of methyldiphenylphosphine oxide (**9**) gave cyclopentanols **8a–d**. Base-catalyzed rearrangement of epoxides **2a–d** and/or **5a–d** led to 3-(disubstitutedphosphinoyl)cyclopent-2-en-1-ols (**7a–d**) which on reaction with the lithium derivative of **9** gave also **8a–d**. The relative configurations of **2a** and **8b–d** were obtained by single crystal X-ray diffraction analysis.

1. Introduction

Application of chiral diphosphine ligands in transition metal-catalyzed asymmetric processes has been extensively studied in the past two decades.[1] This activity has led to the discovery of a number of highly enantioselective chiral phosphine-based catalysts which have been used in the pharmaceutical industry for the synthesis of enantiopure drugs.[2]

As part of our interest on the synthesis and applications in asymmetric catalysis of 1,4-diphosphines we planned the synthesis of a series of diphosphines of general structure **1** (Fig. 1). The hydroxyl group of compounds **1** could be of interest to develop polymer-based chiral ligands and to separate the racemic mixture via diastereomeric derivatives at an appropriate stage of the synthesis.

Lithiated alkyldiphenylphosphine oxides react with epoxides

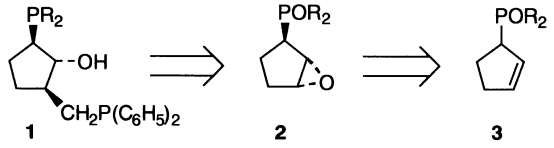


Figure 1. Retrosynthetic analysis of diphosphine **1**.

to give γ-(hydroxyalkyl)phosphine oxides in good yields.[3] Thus, we imagined the synthesis of diphosphines of general structure **1** by regioselective opening of *trans*-epoxides **2** which could be obtained from (2-cyclopentenyl)phosphine oxides (**3**) (Fig. 1).

2. Results and discussion

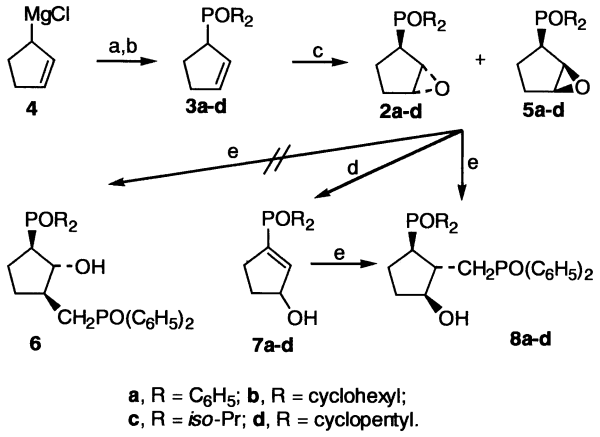
Reaction of an excess of (2-cyclopentenyl)magnesium chloride (**4**) with diphenyl- or dialkyl-chlorophosphines gave, after air oxidation, phosphine oxides **3a–d**, in medium to high yields.[4]

Epoxidation of **3a–d** with *m*-chloroperbenzoic acid (*m*-CPBA)[5] gave a stereoisomeric mixture of the corresponding epoxides **2a–d** and **5a–d** in quantitative yields, which could be easily separated by column chromatography, the *trans* stereoisomer being always the main component. The *trans* arrangement of **2a** was established by spectroscopic means and by single crystal X-ray diffraction analysis, while in the case of **2b–d**, comparison of their ^{1}H and ^{13}C NMR data with those of **2a** was conclusive. Several of these epoxides crystallized in hydrated form, as it was shown by their elemental analyses.

When epoxide **2c** hemihydrate was reacted for the first time with the lithium derivative of methyldiphenylphosphine oxide (**9**), generated from **9** (1 equiv.) and an excess of *n*-butyllithium (1.6 equiv.) in anhydrous THF, allylic alcohol **7c** (19% yield) and starting **9** (91% yield) were the only

Keywords: phosphine oxides; Michael reaction; epoxide.
* Corresponding author. Tel.: +34-93-402-4536; fax: +34-93-403-5941; e-mail: camps@farmacia.far.ub.es

0040–4020/02/$ - see front matter
PII: S0040-4020(02)00314-9



Scheme 1. *Reagents and conditions*: (a) R_2PCl, anh. THF, 0°C; (b) air; (c) *m*-CPBA (20% molar excess), CH_2Cl_2, 25°C, 18 h; (d) KOH, EtOH, 25°C, 18 h; (e) lithium derivative of methyldiphenyphosphine oxide (**9**) (from **9** in anh. THF and 1.6 M *n*-BuLi in hexanes).

isolated products, after column chromatography of the crude reaction mixture. Since no other products derived from epoxide **2c** were isolated, the low yield of **7c** might be associated to its high polarity that would make difficult its extraction from the aqueous phase. Formation of **7c** could be explained by abstraction of the acidic cyclopentyl α-phosphinoyl proton followed by cleavage of the vicinal C–O bond.[6] This transformation could be induced by any base present in the reaction medium. In fact, the allylic alcohol **7c** was obtained in good yield when the above reaction was carried out in the absence of **9**. Also, reaction of **2c** with ethanolic KOH gave **7c** in 98% yield. The same product **7c** was also obtained (95% yield) on treatment of the stereoisomeric epoxide **5c** with ethanolic KOH.

When anhydrous epoxide **2c** (azeotropic distillation of water with toluene in a Dean–Stark equipment) was reacted with the lithium derivative of **9** as before, a diphosphine dioxide was obtained (67% yield), whose ^1H and ^{13}C NMR spectra showed it not to be the expected product **6c**, but the isomeric 3-(diisopropylphosphinoyl)-2-[(diphenylphosphinoyl)methyl]-1-cyclopentanol. Although the relative configuration of this compound could not be deduced from the NMR data, the single crystal X-ray diffraction analysis showed it to be the (*t*-2,*c*-3,*r*-1)-stereoisomer (**8c**).

Moreover, the same product **8c** was obtained (92% yield) on reaction of the stereoisomeric anhydrous compound **5c**, with the lithium derivative of **9**. The fact that the same product **8c** was obtained starting whether from **2c** or **5c** suggests that both reactions occur through a common intermediate. Taking into account the isolation of the allylic alcohol **7c** as a byproduct, the lithium derivative of **7c** could be the common intermediate in these reactions, whose conversion to **8c** might take place regioselectively through a Michael addition of the lithium derivative of **9** to the β-position of the lithium salt of the unsaturated α,β-phosphine oxide **7c**. The stereoselectivity of this addition could be first kinetically controlled by the lithiated hydroxy group of **7c** (*anti*-addition) followed by thermodynamically controlled protonation of the intermediate α-phosphinoyl carbanion[6] to give the more stable (*t*-2,*c*-3,*r*-1)-**8c**. When allylic alcohol **7c** was reacted with the lithium derivative of **9** under similar reaction conditions, **8c** was obtained (56% yield), thus confirming the hypothesis of the intermediacy of the lithium derivative of **7c** in the conversions of **2c** and **5c** to **8c** (Scheme 1).

Similarly, reaction of the anhydrous *trans*-epoxide **2b** with the lithium derivative of **9** gave, after column chromatography, diphosphine dioxide **8b** (74% yield) and allylic alcohol **7b** (14% yield). Compound **8b** was alternatively obtained in high yield by reaction of **7b** with the lithium derivative of **9**. Alcohol **7b** was isolated in low yield (27%) from the reaction of **2b** with *n*-butyllithium and in excellent yield (98%) from **5b** by reaction with ethanolic KOH.

Also, compounds **8a** and **8d** were obtained in good yields (87.5 and 95%, respectively) by reaction of the stereoisomeric mixtures of epoxides **2a/5a** and **2d/5d** with the lithium derivative of **9**. Alternatively, the above mixtures of epoxides were transformed into the corresponding allylic alcohols **7a** and **7d** (99 and 76% yield, respectively) by reaction with ethanolic KOH which, on treatment with the lithium derivative of **9**, gave **8a** and **8d** (87 and 90% yield, respectively).

The relative configurations of compounds **8b** and **8d** were obtained by X-ray diffraction analysis, while that of **8a** was assigned by comparison of its NMR data with those of **8b** and **8d**.

Assignment of the ^1H and ^{13}C NMR spectra of the new compounds herein described was carried out on the basis of the COSY $^1H/^1H$, COSY $^1H/^{13}C$, NOESY and DEPT experiments. In the cases of compounds **3a–d** and **7a–d**, assignment was straightforward. Differentiation of the stereoisomeric epoxides **2a–d** from **5a–d** was carried out by comparison of the NMR data of each compound with those of **2a**, whose *trans*-arrangement was established by single crystal X-ray diffraction analysis (Fig. 2).

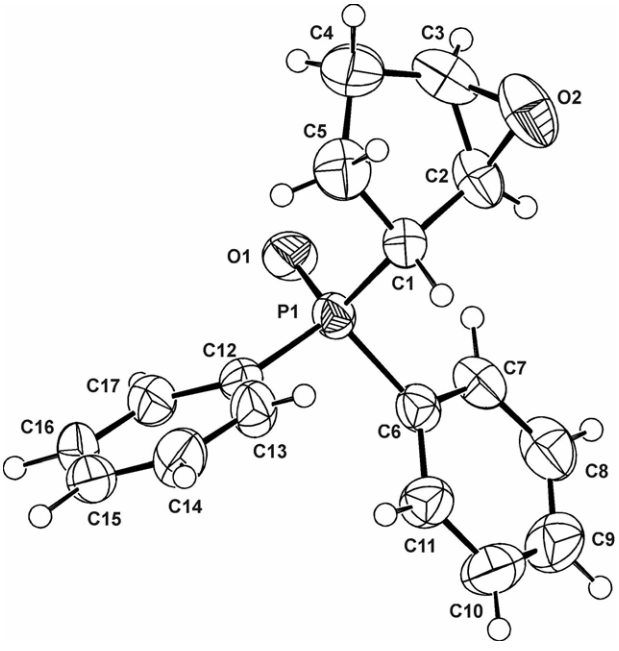


Figure 2. X-Ray diffraction structure (ORTEP) of **2a**.

Table 1. Significant $^3J(^{13}C-^{31}P)$ values for compounds **5a–d**

$^3J(^{13}C-^{31}P)$	**5a**	**5b**	**5c**	**5d**
C3–P	6.6	9.0	8.8	10.9
C4–P	9.7	10.6	10.6	10.3

The conformation of **2a** in the solid state contains an envelope cyclopentane ring in which C5 is out of the plane containing the rest of cyclopentanic carbon atoms and is close to the oxiranic oxygen atom, with the diphenylphosphinoyl substituent in a *pseudoaxial* arrangement. Assignment of the ^{1}H NMR spectra of compounds **2a–d** was carried out by assuming that all of them exist preferentially in $CDCl_3$ solution in a conformation similar to that observed for **2a** in the solid state. Similarly, assignment of the ^{1}H NMR spectra of compounds **5a–d** was carried out by assuming a similar conformation to that of **2a–d**, except for the diphenylphosphinoyl substituent which occupies a *pseudoequatorial* position.

Worthy of note, the observed $^3J(^{13}C-^{31}P)$ coupling constant values were of diagnostic interest to confirm the assigned conformations, since they follow a Karplus relationship.[7,8] Thus, C3 and C4 in compounds **2a–d** appear as singlets, showing that their $^3J(^{13}C-^{31}P)$ coupling constants are close to 0 Hz in accord with dihedral angles C3–C2–C1–P and C4–C5–C1–P close to 90°. The above dihedral angles for **2a** obtained from the single crystal X-ray diffraction structure were 107.3 and 95.9°, respectively.

In the cases of compounds **5a–d**, if the assumed preferred conformations with the phosphinoyl substituents in *pseudo-equatorial* arrangement were correct, the $^3J(^{13}C-^{31}P)$ coupling constant values of C3 and C4 must be much higher because the C3–C2–C1–P and C4–C5–C1–P dihedral angles would be close to 180°. In fact, this is the case, as can be seen from the $^3J(^{13}C-^{31}P)$ values corresponding to C3 and C4 of **5a–d**, collected in Table 1.

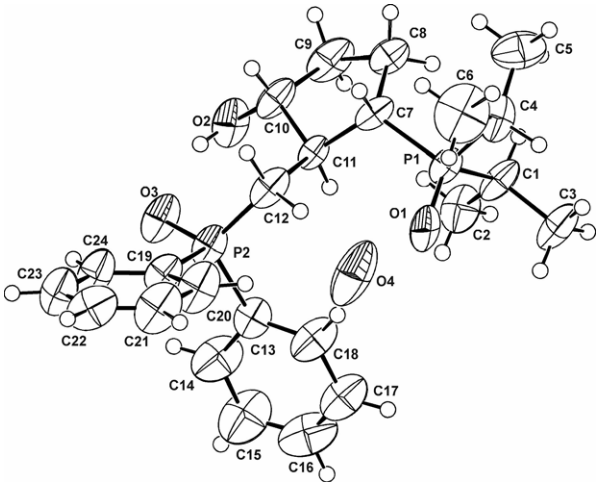


Figure 3. X-Ray diffraction structure (ORTEP) of **8c**.

In the case of diphosphine dioxides **8a–d**, assignment was carried out by assuming that the preferred conformation of these compounds in $CDCl_3$ solution was similar to that observed for **8b–d** in the solid state, in which the cyclopentane ring adopts an envelope conformation with the C2 atom out of the plane defined by the rest of cyclopentanic carbon atoms with all of the substituents in *pseudoequatorial* positions and an intramolecular hydrogen bond between the hydroxyl group and the oxygen atom of the (diphenylphosphinoyl)methyl group through a seven-membered ring, as shown in Fig. 3 for **8c**. All of the single crystals of compounds **8b–d** correspond to their monohydrates, the water molecules (corresponding oxygen atom O4 for **8c**, shown in Fig. 3) establishing hydrogen bonds with the 3-phosphinoyl oxygen atoms.

As before, the observed $^3J(^{13}C-^{31}P)$ values were of diagnostic interest to confirm the assigned conformations. Significant $^3J(^{13}C-^{31}P)$ values for compounds **8a–d** together with the corresponding dihedral angles obtained from the single crystal X-ray diffraction structures of **8b–d** are collected in Table 2. The results in Table 2 confirm the preferred conformation of compounds **8a–d** in $CDCl_3$ solution to be similar to those observed for compounds **8b–d** in the solid state.

Although the conjugate addition to α,β-unsaturated carbonyl compounds is a well established reaction, there is little information in the literature regarding conjugate additions to α,β-unsaturated phosphinoyl compounds.[9] It is known that amines,[10,11] amides,[11] organocuprates[12] and silyl cuprates[13] add to the electrophilic double bond of achiral vinyl phosphine oxides. Moreover, Warren et al.,[14] have recently described the diastereoselective conjugated addition of hydrogen, carbon, silicon, sulfur, nitrogen and oxygen nucleophiles to acyclic γ-oxygenated chiral vinyl phosphine oxides to give β-substituted phosphine oxides. However, the diastereoselective nucleophilic addition of a phosphinoylmethyl group to a cyclic vinyl phosphine oxide to give a 1,3-diphosphine dioxide with stereocontrolled formation of two new stereogenic centers, as in the examples herein reported, has no precedent.

Preliminary studies carried out with enantioenriched **7a** (44% ee)[15] showed its reaction with the lithium derivative of **9** to take place without racemization. This result opens

Table 2. Significant $^3J(^{13}C-^{31}P)$ values (Hz) for compounds **8a–d** and dihedral angles (°) (from the single crystal X-ray diffraction structures) for compounds **8b–d**

$^3J(^{13}C-^{31}P)$ (dihedral angle)	**8a**	**8b**	**8c**	**8d**
*C*1–C3–*P*OR_2 (C1–C2–C3–P)	10.6	11.6 (162.6)	11.6 (158.0)	12.3 (157.8)
*C*1–CH_2*P*O(C_6H_5)$_2$ (C1–C2–CH_2–P)	2.7	≈0 (67.1)	≈0 (74.3)	≈0 (64.3)
*C*3–CH_2*P*O(C_6H_5)$_2$ (C3–C2–CH_2–P)	12.8	14.2 (177.0)	14.2 (168.4)	14.5 (179.9)
*C*5–C3–*P*OR_2 (C5–C4–C3–P)	4.3	5.6 (152.3)	6.0 (134.6)	6.4 (132.0)
CH_2–C3–*P*OR_2 (C5–C4–C3–P)	≈0	≈0 (74.4)	≈0 (78.1)	≈0 (78.9)

the way for the preparation of enantiopure diphosphine dioxides **8**, from which the corresponding 1,3-diphosphines could be obtained. This kind of diphosphines have rarely been used as ligands for metal-catalyzed asymmetric reactions.[16]

3. Experimental

3.1. General

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: ^{1}H 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). ^{1}H and ^{13}C NMR chemical shifts (δ) are reported in ppm related 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; h, heptuplet. For the different cyclopentanic compounds, the term H_α or H_β are assigned to hydrogen atoms which are *cis* or *trans*, respectively, relative to the substituent at position 1. In compounds **8a**–**d**, the terms H_{syn} or H_{anti} refer to the protons of the $CH_2PO(C_6H_5)_2$ methylene group, which in the assumed preferred conformation are *syn* or *anti*, respectively, to the 2-H atom. IR spectra were recorded on a FT/IR Perkin–Elmer spectrometer, model 1600; only strong or medium intensity 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-meter HP-5 (5% diphenyl–95% dimethyl-polysiloxane) column [conditions: 10 psi, initial temperature: 100°C (2 min), then heating at a rate of 10°C/min till 250°C, then isothermic] 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. 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. Chlorodiisopropylphosphine and chlorodiphenyl-phosphine were purchased from Aldrich Chemical Co. and chlorodicyclohexylphosphine was purchased from Strem Chemical Inc. Chlorodicyclopentylphosphine was prepared according to the method previously described.[17]

3.1.1. (2-Cyclopentenyl)diphenylphosphine oxide (3a). To a suspension of Mg turnings (9.1 g, 0.37 mol) and a catalytic amount of I_2 in anhydrous THF (90 mL) at −20°C, was added dropwise 3-chlorocyclopentene (28.7 mL, 97% content, 0.29 mol) in anhydrous THF (90 mL). The mixture was stirred at −10°C for 5 h and the filtered suspension was added via cannula to a cold solution (ice-bath) of chlorodiphenylphosphine (5.70 mL, 7.00 g, 32 mmol) in anhydrous THF (60 mL). When the addition was over, the ice-bath was removed and the mixture was stirred at room temperature for 18 h. The mixture was cooled (ice-bath), treated with saturated aqueous solution of NH_4Cl (50 mL), made acidic (pH=1) with 5N H_2SO_4 (35 mL), and concentrated in vacuo to give an oily residue, which was stirred with hexane (200 mL) for 2 h. The hexane solution was discarded and the hexane insoluble material was dissolved in H_2O (100 mL), the solution was made strongly basic with 5N NaOH (150 mL) and was concentrated in vacuo to give a residue which was extracted by stirring with ethyl acetate (3×200 mL) for 2 h each time. The organic extracts were dried (Na_2SO_4), filtered and evaporated under reduced pressure to give **3a** as a pale brown solid (7.24 g). Standard column chromatography [silica gel (150 g), ethyl acetate] gave pure **3a** (3.82 g, 45% yield). The analytical sample of **3a** was obtained as a white solid by crystallization (hexane/ethyl acetate 3:1), mp 125–126°C. IR (KBr), ν_{max}: 3054, 2939, 1436, 1180, 1118, 1071, 918, 750, 723, 701, 640 cm^{-1}; ^{1}H NMR, δ=7.79–7.71 (complex signal, 4H, diastereotopic Ar-H_{ortho}), 7.51–7.47 (complex signal, 2H, diastereotopic Ar-H_{para}), 7.46–7.40 (complex signal, 4H, diastereotopic Ar-H_{meta}), 5.91 (m, 1H, 3-H), 5.55–5.52 (m, 1H, 2-H), 3.71–3.64 (m, 1H, 1-H), 2.39–2.09 (complex signal, 4H, 4-H_α, 4-H_β, 5-H_α, 5-H_β); ^{13}C NMR, δ=135.7 (CH, d, $^2J_{C-P}$=11.6 Hz, C3), 132.7 (C, d, $^1J_{C-P}$=95.2 Hz) and 131.8 (C, d, $^1J_{C-P}$=94.2 Hz) (diastereotopic Ar-C_{ipso}), 131.4 (CH, broad s, Ar-CH_{para}), 131.2 (CH, d, $^2J_{C-P}$=8.6 Hz) and 131.0 (CH, d, $^2J_{C-P}$=8.6 Hz) (diastereotopic Ar-CH_{ortho}), 128.3 (CH, d, $^3J_{C-P}$=11.1 Hz) and 128.2 (CH, d, $^3J_{C-P}$=11.2 Hz) (diastereotopic Ar-CH_{meta}), 125.3 (CH, d, $^3J_{C-P}$=6.0 Hz, C2), 46.1 (CH, d, $^1J_{C-P}$=72.4 Hz, C1), 32.6 (CH_2, d, $^3J_{C-P}$=2.0 Hz, C4), 23.6 (CH_2, s, C5); ^{31}P NMR, δ=32.8; MS (EI), *m/z* (%): 268 ($M^{\cdot+}$, 8), 202 [$HPO(C_6H_5)_2^{\cdot+}$, 100], 201 [$PO(C_6H_5)_2^+$, 43], 155 (24), 77 ($C_6H_5^+$, 48), 67 ($C_5H_7^+$, 33). Anal. calcd for $C_{17}H_{17}OP$: C, 76.11; H, 6.39. Found: C, 75.82; H, 6.48.

3.1.2. Dicyclohexyl-(2-cyclopentenyl)phosphine oxide (3b). To a suspension of Mg turnings (9.72 g, 0.40 mol) and a catalytic amount of I_2 in anhydrous THF (120 mL) at −10°C, was added dropwise 3-chlorocyclopentene (32.8 mL, 90% content, 0.28 mol) in anhydrous THF (120 mL). The mixture was stirred at −10°C for 5 h and the filtered suspension was added via cannula to a cold solution (ice-bath) of chlorodicyclohexylphosphine and diethyl ether [ratio 1.1:1 (^{1}H NMR), 9.48 g, 31.6 mmol] in anhydrous THF (100 mL). When the addition was over, the ice-bath was removed and the mixture was stirred at room temperature for 18 h. The mixture was cooled (ice-bath), treated with saturated aqueous solution of NH_4Cl (50 mL), made acidic (pH=1) with 2N H_2SO_4 (28 mL), and concentrated in vacuo to give a yellow oily residue, which was stirred with hot diethyl ether (400 mL) for 2 h. The ethereal solution was discarded and the ether insoluble residue was dissolved in H_2O (150 mL), was made basic with 5N NaOH (40 mL) and was stirred with ethyl acetate (400 mL) for 36 h. The organic layer was separated, dried (Na_2SO_4), filtered and evaporated in vacuo to give impure **3b** as a dark viscous oil (5.12 g). The aqueous layer was stirred with ethyl acetate (400 mL) for 48 h, the organic phase was separated, dried (Na_2SO_4), filtered and evaporated to give a further amount of impure **3b** (1.71 g), that was combined with the previous extract. Part of this product (580 mg) was submitted to flash column chromatography

[silica gel (53 g), ethyl acetate/methanol mixtures]. On elution with a mixture of ethyl acetate/methanol in the ratio of 99:1, pure **3b** (280 mg) was obtained as a pale yellow oil (37% yield). The analytical sample of **3b** was obtained as a colorless oil by distillation (100°C/1.0 Torr). IR (KBr), ν_{max}: 3147 (OH st, H_2O) 2924, 2849, 1445, 1404, 1212, 1158, 1116, 918, 891, 852, 726 cm^{-1}; ^1H NMR, δ= 5.99 (dq, J=5.5, 2.5 Hz, 1H, 3-H), 5.74 (dq, J=5.5, 2.5 Hz, 1H, 2-H), 3.23–3.15 (m, 1H, 1-H), 2.56–2.39 (complex signal, 2H, 4-H_α and 4-H_β), 2.28–2.11 (complex signal, 2H, 5-H_α and 5-H_β), 2.00–1.79 (complex signal, 10H), 1.77–1.67 (complex signal, 2H), 1.51–1.37 (complex signal, 4H) and 1.31–1.18 (complex signal, 6H) (cyclohexyl H); ^{13}C NMR, δ=133.7 (CH, d, $^3J_{C-P}$=10.0 Hz, C3), 127.1 (CH, d, $^2J_{C-P}$=5.1 Hz, C2), 42.7 (CH, d, $^1J_{C-P}$=61.3 Hz, C1), 36.0 (CH, d, $^1J_{C-P}$=61.4 Hz) and 35.8 (CH, d, $^1J_{C-P}$= 61.3 Hz) (diastereotopic cyclohexyl CH), 32.5 (CH_2, d, $^3J_{C-P}$=3.0 Hz, C4), 26.8–25.9 (CH_2, complex signal, cyclohexyl CH_2), 23.7 (CH_2, broad s, C5); ^{31}P NMR, δ=49.0; MS (EI), m/z (%): 280 ($M^{\cdot+}$, 9), 214 [$(M-C_5H_6)^{\cdot+}$, 75], 213 [$(M-C_5H_7)^+$, 19], 199 [$(M+H-C_6H_{10})^+$, 14], 133 (90), 132 [$(M-C_5H_6-C_6H_{10})^{\cdot+}$, 71), 83 ($C_6H_{11}^+$, 42), 81 (40), 67 ($C_5H_7^+$, 82), 55 ($C_4H_7^+$, 100). Anal. calcd for $C_{17}H_{29}OP\cdot1.1H_2O$: C, 68.01; H, 10.48. Found: C, 67.80; H, 10.33.

3.1.3. (2-Cyclopentenyl)diisopropylphosphine oxide (3c). To a suspension of Mg turnings (4.86 g, 0.20 mol) and a catalytic amount of I_2 in anhydrous THF (50 mL) at −10°C was added dropwise 3-chlorocyclopentene (17.6 g, containing 10% of cyclopentadiene, 160 mmol) in anhydrous THF (50 mL). The mixture was stirred for 5 h at −10°C and the filtered suspension was added via cannula to a cold (ice-bath) solution of chlorodiisopropylphosphine (2.7 mL, 2.49 g, 96% content, 16.3 mmol) in anhydrous THF (100 mL). When the addition was over, the ice-bath was removed and the mixture was stirred at room temperature for 18 h. The mixture was cooled (ice-bath), treated with saturated aqueous solution of NH_4Cl (25 mL), made acidic (pH=1) with 2N H_2SO_4 (10 mL) and concentrated in vacuo to give a residue, which was stirred with hot diethyl ether (200 mL) for 2 h. The ethereal solution was discarded and the ether insoluble residue was dissolved in H_2O (100 mL), was made basic with 5N NaOH (30 mL) and was stirred for 1 h with ethyl acetate (200 mL). The organic layer was separated, dried (Na_2SO_4), filtered and evaporated in vacuo to give impure **3c** as a dark oil [2.22 g, 78% relative area by GLC/MS]. The aqueous layer was extracted with ethyl acetate (2×100 mL) and the combined organic extracts were dried (Na_2SO_4), filtered and evaporated under reduced pressure to give a further amount of impure **3c** (0.56 g, 90% relative area by GLC/MS, 68% approximate global yield). The analytical sample of **3c** was obtained as a colorless oil by distillation (90°C/0.5 Torr). IR (KBr), ν_{max}: 3425 (OH st, H_2O), 3054, 2961, 2934, 2874, 1464, 1172, 1149, 1025, 986, 926, 884, 687 cm^{-1}; ^1H NMR, δ=5.90 (dq, J=5.0, 2.5 Hz, 1H, 3-H), 5.74 (dq, J=6.0, 2.5 Hz, 1H, 2-H), 3.25–3.17 (m, 1H, 1-H), 2.56–2.40 (complex signal, 2H, 4-H_α and 4-H_β), 2.30–2.14 (complex signal, 2H, 5-H_α and 5-H_β), 2.11 (dh, J=10.0, 7.0 Hz, 1H) and 2.08 (dh, J=11.0, 7.0 Hz, 1H) [diastereotopic CH(CH_3)$_2$], 1.90 (broad s, H_2O), 1.24 (dd, J=7.5, 14.0 Hz, 3H), 1.22 (dd, J=7.5, 14.5 Hz, 3H), 1.208 (dd, J=7.5, 14.5 Hz, 3H) and 1.207 (dd, J=7.5, 14.5 Hz, 3H) [diastereotopic CH(CH_3)$_2$]; ^{13}C NMR, δ=133.8 (CH, d, $^3J_{C-P}$=10.2 Hz, C3), 127.2 (CH, d, $^2J_{C-P}$=4.7 Hz, C2), 42.7 (CH, d, $^1J_{C-P}$=60.9 Hz, C1), 32.5 (CH_2, d, $^3J_{C-P}$= 3.0 Hz, C4), 25.4 (CH, d, $^1J_{C-P}$=61.0 Hz) and 25.2 (CH, d, $^1J_{C-P}$=61.3 Hz) [diastereotopic CH(CH_3)$_2$], 23.7 (CH_2, broad s, C5), 16.5–16.2 [CH_3, overlapped d, diastereotopic CH(CH_3)$_2$]; ^{31}P NMR, δ=56.4; MS (EI), m/z (%): 200 ($M^{\cdot+}$, 14), 158 [$(M-C_3H_6)^{\cdot+}$, 2] 157 [$(M-C_3H_7)^+$, 2], 134 [$(M-C_5H_6)^{\cdot+}$, 88], 92 [$(C_3H_7POH_2)^{\cdot+}$, 100], 91 (12), 67 ($C_5H_7^+$, 34). Anal. calcd for $C_{11}H_{21}OP\cdot2/5H_2O$: C, 63.68; H, 10.60. Found: C, 63.87; H, 10.36.

3.1.4. (2-Cyclopentenyl)dicyclopentylphosphine oxide (3d). To a suspension of Mg turnings (8.8 g, 0.36 mol) and a catalytic amount of I_2 in anhydrous THF (90 mL) at −10°C was added dropwise 3-chlorocyclopentene (32.0 g, containing 7% of cyclopentadiene, 0.29 mol) in anhydrous THF (90 mL). The mixture was stirred for 6 h at −10°C and the filtered suspension was added via cannula to a cold (ice-bath) solution of the chlorodicyclopentylphosphine[17] (5.93 g, 29 mmol) in anhydrous THF (60 mL). When the addition was over, the ice-bath was removed and the mixture was stirred at room temperature for 18 h. The mixture was cooled (ice-bath), treated with saturated aqueous solution of NH_4Cl (48 mL), made acidic (pH=1) with 5N H_2SO_4 (150 mL) and concentrated in vacuo to give a residue, which was stirred with hexane (200 mL) for 2 h. The hexanic solution was dried (Na_2SO_4), filtered and evaporated in vacuo to give impure **3d** as a brown oil (2.27 g). The hexane insoluble material was dissolved in H_2O (100 mL), made basic with 5N NaOH (200 mL) and extracted with ethyl acetate (3×200 mL). The combined organic extracts were dried (Na_2SO_4), filtered and evaporated in vacuo to give a further amount of impure **3d** (3.43 g, 80% approximate global yield). This compound could not be fully purified and was used as such in the next stage. ^1H NMR (300 MHz) δ=5.88 (m, 1H, 3-H), 5.76 (m, 1H, 2-H), 3.20 (m, 1H, 1-H), 2.46 (m, 2H, 4-H_α and 4-H_β), 2.2–1.5 (complex signal, 20H, cyclopentyl H, 5-H_α and 5-H_β); ^{13}C NMR, δ=133.3 (CH, d, $^3J_{C-P}$=10.6 Hz, C3), 127.5 (CH, d, $^2J_{C-P}$=4.4 Hz, C2), 45.3 (CH, d, $^1J_{C-P}$=64.6 Hz, C1), 36.6 (CH, d, $^1J_{C-P}$=65.5 Hz) and 36.4 (CH, d, $^1J_{C-P}$=65.5 Hz) (diastereotopic cyclopentyl CH), 32.5 (CH_2, d, $^3J_{C-P}$= 3.2 Hz, C4), 27.1–25.8 (complex signal, CH_2, cyclopentyl CH_2), 23.6 (CH_2, s, C5).

3.1.5. Epoxidation of 3a: *cis*- and *trans*-(2,3-epoxycyclopentyl)diphenylphosphine oxide (5a and 2a). A solution of **3a** (1.16 g, 4.3 mmol) in CH_2Cl_2 (40 mL) was added to a cold (ice-bath) solution of *m*-CPBA (2.6 g, 57% content, 8.6 mmol) in CH_2Cl_2 (80 mL) and the mixture was stirred at room temperature for 18 h. The mixture was washed with 10% aqueous solution of $NaHSO_3$ (3×20 mL), saturated aqueous solution of $NaHCO_3$ (3×20 mL), water (10 mL) and brine (10 mL). The organic phase was dried (Na_2SO_4), filtered and evaporated under reduced pressure to give a pale yellow foamy solid (1.15 g). Standard column chromatography of the above solid [silica gel (60 g), ethyl acetate] gave in order of elution: **2a** (0.82 g, 67% yield) and **5a** (0.13 g, 11% yield). The analytical sample of **2a** was obtained as a white solid by crystallization (mixture of ethyl acetate/hexane in the ratio of 5:7), mp 133–134°C. IR (KBr), ν_{max}: 3435 (OH st, H_2O), 3051, 2922, 1436,

1182, 1151, 1118, 926, 838, 723, 695 cm^{-1}; ^1H NMR, δ=7.83–7.78 (m, 2H) and 7.76–7.72 (m, 2H) (diastereotopic Ar-H_{ortho}), 7.54–7.43 (complex signal, 6H, diastereotopic Ar-H_{meta} and Ar-H_{para}), 3.55 (d, J=2.5 Hz, 1H, 3-H), 3.49 (dd, J=2.5, 1.5 Hz, 1H, 2-H), 3.15 (ddd, J=9.0, 6.0, 1.5 Hz, 1H, 1-H), 1.96 (dd, J=13.7, 8.2 Hz, 1H, 4-H_β), 1.95–1.86 (m, 1H, 5-H_α), 1.82–1.75 (m, 1H, 4-H_α), 1.78–1.65 (m, 1H, 5-H_β); ^{13}C NMR, δ=132.1 (C, d, $^1J_{C-P}$= 98.8 Hz) and 132.0 (C, d, $^1J_{C-P}$=95.8 Hz) (diastereotopic Ar-C_{ipso}), 131.9 (CH, d, $^4J_{C-P}$=2.5 Hz) and 131.8 (CH, d, $^4J_{C-P}$=2.5 Hz) (diastereotopic Ar-CH_{para}), 130.8 (CH, d, $^2J_{C-P}$=9.2 Hz, Ar-CH_{ortho}), 128.74 (CH, d, $^3J_{C-P}$=11.0 Hz) and 128.72 (CH, d, $^3J_{C-P}$=11.0 Hz) (diastereotopic Ar-CH_{meta}), 58.6 (CH, s, C3), 57.2 (CH, d, $^2J_{C-P}$=6.1 Hz, C2), 39.2 (CH, d, $^1J_{C-P}$=68.9 Hz, C1), 27.0 (CH_2, s, C4), 20.5 (CH_2, d, $^2J_{C-P}$=4.3 Hz, C5); ^{31}P NMR, δ=32.4; MS (EI), m/z (%): 284 ($M^{\cdot+}$, 1), 283 (4), 228 (33), 202 [[HPO(C_6H_5)$_2$]$^{\cdot+}$, 100], 201 (95), 155 (42), 83 ($C_5H_7O^+$, 20), 77 ($C_6H_5^+$, 100). Anal. calcd for $C_{17}H_{17}O_2P$: C, 71.82; H, 6.03. Found: C, 71.87; H, 6.06. The analytical sample of **5a** was obtained as a white solid by crystallization (mixture of ethyl acetate/hexane in the ratio of 2:1), mp 164–164.5°C. IR (KBr), ν_{max}: 3428 (OH st, H_2O), 3051, 2909, 1436, 1185, 1117, 850, 752, 721, 699 cm^{-1}; ^1H NMR, δ=7.88 (m, 2H) and 7.78 (m, 2H) (diastereotopic Ar-H_{ortho}), 7.56–7.43 (complex signal, 6H, diastereotopic Ar-H_{meta} and Ar-H_{para}), 3.57 (broad d, J=2.0 Hz, 1H, 2-H), 3.47 (broad d, J=2.5 Hz, 1H, 3-H), 2.78 (dddd, J= 12.0, 10.5, 8.0, 1.0 Hz, 1H, 1-H), 2.12 (dd, J=13.5, 7.5 Hz, 1H, 4-H_α), 1.81 (*pseudo* dt, J=12.5, 8.0 Hz, 1H, 5-H_β), 1.68 (m, 1H, 4-H_β), 1.64–1.54 (m, 1H, 5-H_α); ^{13}C NMR, δ= 131.9 (CH, d, $^4J_{C-P}$=2.5 Hz) and 131.8 (CH, d, $^4J_{C-P}$= 3.1 Hz) (diastereotopic Ar-CH_{para}), 132.3 (C, d, $^1J_{C-P}$= 97.6 Hz) and 131.2 (C, d, $^1J_{C-P}$=97.6 Hz) (diastereotopic Ar-C_{ipso}), 131.4 (CH, d, $^2J_{C-P}$=9.1 Hz) and 131.1 (CH, d, $^2J_{C-P}$=9.2 Hz) (diastereotopic Ar-CH_{ortho}), 128.5 (CH, d, $^3J_{C-P}$=11.6 Hz, Ar-CH_{meta}), 56.3 (CH, d, $^3J_{C-P}$=6.7 Hz, C3), 56.2 (CH, s, C2), 41.5 (CH, d, $^1J_{C-P}$=75.0 Hz, C1), 27.5 (CH_2, d, $^3J_{C-P}$=9.7 Hz, C4), 20.0 (CH_2, s, C5); ^{31}P NMR, δ=33.6; MS (EI), m/z (%): 285 (2), 284 ($M^{\cdot+}$, 1), 219 (44), 203 (28), 202 [[HPO(C_6H_5)$_2$]$^{\cdot+}$, 100], 201 (83), 155 (25), 83 ($C_5H_7O^+$, 10), 77 ($C_6H_5^+$, 35). Anal. calcd for $C_{17}H_{17}O_2P{\cdot}1/4H_2O$: C, 70.70; H, 6.11. Found: C, 71.00; H, 6.19.

3.1.6. Epoxidation of 3b: *cis*- and *trans*-dicyclohexyl(2,3-epoxycyclopentyl)phosphine oxide (5b and 2b). From impure **3b** (3.2 g, 48% relative area by GLC/MS, approximately 5.5 mmol) and *m*-CPBA (7.8 g, 57% content, 25.7 mmol), following a similar procedure to that described for **3a**, a mixture of **2b** and **5b** (2.62 g) was obtained. Flash column chromatography [silica gel (75 g), ethyl acetate/methanol mixtures] of the above mixture gave in order of elution: pure **2b** (1.21 g, 74% yield), on elution with a mixture of ethyl acetate/methanol in the ratio of 99:1, a mixture of **2b** and **5b** (60 mg, 3.7% yield) and pure **5b** (0.26 g, 16% yield), on elution with a mixture of ethyl acetate/methanol in the ratio of 97:3. The analytical sample of **2b** was obtained as a white solid by crystallization (ethyl acetate), mp 129–139°C. IR (KBr), ν_{max}: 2932, 2848, 1444, 1211, 1162, 1118, 925, 892, 833 cm^{-1}; ^1H NMR, δ=3.67 (broad d, J=2.0 Hz, 1H, 2-H), 3.60 (m, 1H, 3-H), 2.62 (dt, J=1.5, 9.5 Hz, 1H, 1-H), 2.10–1.64 (complex signal, 16H, 12 cyclohexyl H, 4-H_α, 4-H_β (2.06, dd, J=8.0, 13.0 Hz), 5-H_α, and 5-H_β], 1.46–1.32 (complex signal, 4H) and 1.30–1.17 (complex signal, 6H) (rest of cyclohexyl H); ^{13}C NMR, δ=59.1 (CH, broad s, C3), 57.8 (CH, d, $^2J_{C-P}$= 3.9 Hz, C2), 36.9 (CH, d, $^1J_{C-P}$=61.5 Hz) and 36.3 (CH, d, $^1J_{C-P}$=62.6 Hz) (diastereotopic cyclohexyl CH), 36.0 (CH, d, $^1J_{C-P}$=56.3 Hz, C1), 27.3 (CH_2, broad s, C4), 26.9–25.9 (complex signal, CH_2, cyclohexyl CH_2), 21.0 (CH_2, d, $^2J_{C-P}$=4.1 Hz, C5); ^{31}P NMR, δ=51.0; MS (EI), m/z (%): 296 (M^+, 1), 267 (2), 214 [($M-C_6H_{10}$)$^{\cdot+}$, 16], 199 (14), 186 (16), 133 (25), 132 [($M-2C_6H_{10}$)$^{\cdot+}$, 28], 83 ($C_5H_7O^+$, 45), 55 (100). Anal. calcd. for $C_{17}H_{29}O_2P$: C, 68.89; H, 9.87. Found: C, 68.79; H, 9.99. The analytical sample of **5b** was obtained as a white solid by crystallization (ethyl acetate), m.p. 132–133.5°C. IR (KBr), ν_{max}: 2930, 2846, 1447, 1215, 1158, 1116, 1003, 917, 893, 856 cm^{-1}; ^1H NMR, δ=3.64 (broad d, J=2.0 Hz, 1H, 2-H), 3.53 (broad d, J=2.5 Hz, 1H, 3-H), 2.33 (dddd, J=14.0, 11.0, 8.5, 1.0 Hz, 1H, 1-H), 2.13 (dd, J=13.5, 7.5 Hz, 1H, 4-H_α), 2.04–1.65 (complex signal, 13H, 11 cyclohexyl H, 5-H_α and 5-H_β (1.74, *pseudo* dt, J=12.5, 8.0 Hz)], 1.65–1.42 (complex signal, 6H, 5 cyclohexyl H and 4-H_β (1.62, dddd, J=14.0, 9.5, 8.0, 1.0 Hz)], 1.32–1.18 (complex signal, 6H, rest of cyclohexyl H); ^{13}C NMR, δ=57.0 (CH, s, $^3J_{C-P}$=10.6 Hz, C3), 56.2 (CH, d, $^2J_{C-P}$=3.4 Hz, C2), 38.0 (CH, d, $^1J_{C-P}$=61.0 Hz, C1), 35.9 (CH, d, $^1J_{C-P}$=62.8 Hz) and 35.7 (CH, d, $^1J_{C-P}$=62.7 Hz) (diastereotopic cyclohexyl CH), 27.2 (CH_2, d, $^3J_{C-P}$=9.0 Hz, C4), 26.8–25.4 [complex signal, CH_2, cyclohexyl CH_2], 20.4 (CH_2, s, C5); ^{31}P NMR, δ=51.9; MS (EI), m/z (%): 296 ($M^{\cdot+}$, 1), 214 [($M-C_6H_{10}$)$^{\cdot+}$, 6], 148 (14), 133 (9), 132 [($M-2C_6H_{10}$)$^{\cdot+}$, 7], 83 ($C_6H_{11}^+$, 33), 67 ($C_5H_7^+$, 100). Anal. calcd for $C_{17}H_{29}O_2P$: C, 68.89; H, 9.87. Found: C, 68.63; H, 9.81.

3.1.7. Epoxidation of 3c: *cis*- and *trans*-(2,3-epoxycyclopentyl)diisopropylphosphine oxide (5c and 2c). From **3c** (300 mg, 1.5 mmol) and *m*-CPBA (540 mg, 57% content, 1.8 mmol) and following the procedure described for **3a**, a mixture of **2c** and **5c** (0.29 g) was obtained as a yellow oil. Standard column chromatography [silica gel (30 g), mixtures of ethyl acetate/methanol] of the above product gave, in order of elution: **2c** (200 mg, 62% yield) and a mixture of **2c** and **5c** (10 mg, 3% yield), on elution with a mixture ethyl acetate/methanol in the ratio of 97.8:2.2, and **5c** (50 mg, 15% yield), on elution with a mixture of ethyl acetate/methanol in the ratio of 97.6:2.4. The analytical sample of **2c** as a colorless oil was obtained by distillation (90°C/0.5 Torr). IR (KBr), ν_{max}: 3423 (OH st, H_2O), 2961, 2935, 2876, 1466, 1390, 1175, 1147, 1022, 928, 885, 838, 706 cm^{-1}; ^1H NMR, δ=3.61 (broad d, J=2.5 Hz, 1H, 2-H), 3.55 (broad d, J=2.5 Hz, 1H, 3-H), 2.61 (dt, J=1.0, 9.5 Hz, 1H, 1-H), 2.20–2.08 (broad signal, H_2O), 2.08 (dh, J=12.5, 7.5 Hz, 1H) and 2.03 (dh, J=10.5, 7.5 Hz, 1H) [diastereotopic C*H*(CH_3)$_2$], 2.01 (broad dd, J=14.0, 9.5 Hz, 1H, 4-H_β), 1.90 (broad dt, J=9.5, 13.5 Hz, 1H, 5-H_α), 1.83 (ddt, J=14.0, 1.0, 9.0 Hz, 1H, 4-H_α), 1.73–1.62 (m, 1H, 5-H_β), 1.19 (dd, J=15.0, 7.5 Hz, 3H), 1.18 (dd, J=15.0, 7.5 Hz, 3H), 1.16 (dd, J=15.0, 7.5 Hz, 3H), 1.15 (dd, J= 15.0, 7.5 Hz, 3H) [diastereotopic CH(C*H*$_3$)$_2$]; ^{13}C NMR, δ=59.0 (CH, broad s, C3), 57.7 (CH, d, $^2J_{C-P}$=4.1 Hz, C2), 36.0 (CH, d, $^1J_{C-P}$=55.8 Hz, C1), 27.2 (CH_2, s, C4), 26.0 (CH, d, $^1J_{C-P}$=61.8 Hz) and 25.5 (CH, d, $^1J_{C-P}$=

62.8 Hz) [diastereotopic *C*H(CH_3)$_2$], 20.9 (CH_2, d, $^2J_{C-P}$= 3.8 Hz, C5), 16.4–16.2 [complex signal, CH_3, diastereotopic CH(*C*H_3)$_2$]; ^{31}P NMR, δ=56.1; MS (EI), *m/z* (%): 217 [(M+H)$^+$, 3], 215 [(M−H)$^+$, 6], 175 (8), 174 [(M−C_3H_6)$^{\cdot+}$, 7], 173 (16), 146 [(M−C_3H_6–CO)$^{\cdot+}$, 36], 134 [(M−C_5H_6O)$^{\cdot+}$, 73], 92 ($C_3H_7POH_2^{\cdot+}$, 100), 83 ($C_5H_7O^+$, 29). Anal. calcd for $C_{11}H_{21}O_2P\cdot1/2H_2O$: C, 58.65; H, 9.85. Found: C, 58.53; H, 9.83. The analytical sample of **5c** as a colorless viscous oil was obtained by distillation (90°C/0.5 Torr). IR (KBr), ν_{max}: 3294 (OH st, H_2O), 2961, 2936, 2876, 1466, 1173, 1146, 1025, 885, 851, 695, 643 cm^{-1}; ^{1}H NMR, δ=3.69 (broad d, *J*= 2.0 Hz, 1H, 2-H), 3.57 (broad d, *J*=2.5 Hz, 1H, 3-H), 2.37 (dddd, *J*=14.0, 11.0, 8.0, 1.5 Hz, 1H, 1-H), 2.21 [dh, *J*= 11.0, 7.0 Hz, 1H, diastereotopic C*H*(CH_3)$_2$], 2.16 (broad dd, *J*=13.0, 7.5 Hz, 1H, 4-H$_\alpha$), 2.14 [dh, *J*=9.5, 7.0 Hz, 1H, diastereotopic C*H*(CH_3)$_2$], 2.03 (broad s, H_2O), 1.79 (broad dt, *J*=12.0, 8.0 Hz, 1H, 5-H$_\beta$), 1.67 (dddd, *J*=14.0, 10.0, 8.5, 1.5 Hz, 1H, 4-H$_\beta$), 1.57 (dddt, *J*=12.0, 10.0, 7.5, 11.0 Hz, 1H, 5-H$_\alpha$), 1.30 (dd, *J*=14.5, 7.0 Hz, 3H), 1.281 (dd, *J*=14.5, 7.0 Hz, 3H), 1.280 (dd, *J*=14.5, 7.0 Hz, 3H), 1.26 (dd, *J*=14.5, 7.0 Hz, 3H) [diastereotopic CH(C*H*$_3$)$_2$]; ^{13}C NMR, δ=56.9 (CH, d, $^3J_{C-P}$=10.6 Hz, C3), 56.1 (CH, d, $^2J_{C-P}$=3.3 Hz, C2), 37.9 (CH, d, $^1J_{C-P}$=60.8 Hz, C1), 27.2 (CH_2, d, $^3J_{C-P}$=8.8 Hz, C4), 24.3 [CH, d, $^1J_{C-P}$= 62.8 Hz, diastereotopic *C*H(CH_3)$_2$], 20.3 (CH_2, s, C5), 16.0–15.6 [complex signal, CH_3, diastereotopic CH(*C*H_3)$_2$]; ^{31}P NMR, δ=57.1; MS (EI), *m/z* (%): 217 (1), 216 (M$^{\cdot+}$, 0.6), 174 [(M−C_3H_6)$^{\cdot+}$, 2], 173 (2), 134 [(M−C_5H_6O)$^{\cdot+}$, 18], 92 ($C_3H_7POH_2^{\cdot+}$, 26), 67 ($C_5H_7^+$, 100). Anal. calcd for $C_{11}H_{21}O_2P\cdot2/3H_2O$: C, 57.91; H, 9.87. Found: C, 58.02; H, 9.81.

3.1.8. Epoxidation of 3d: *cis*- and *trans*-dicyclopentyl-(2,3-epoxycyclopentyl)phosphine oxide (5d and 2d). From impure **3d** (3.43 g, approximately 13.6 mmol) and *m*-CPBA (4.94 g, 57% content, 16.3 mmol) and following the procedure described for **3a**, a mixture of **2d** and **5d** (2.76 g) was obtained as an oil. Standard column chromatography [silica gel (150 g), ethyl acetate/methanol mixtures] of the above product gave in order of elution: **2d** (1.58 g, 43% yield) and **5d** (0.43 g, 12% yield) on elution with a mixture of ethyl acetate/methanol in the ratio of 21:1. The analytical sample of **2d** was obtained as a white solid by crystallization (hexane), mp 130.5–131.5°C. IR (NaCl), ν_{max}: 3358 (OH st, H_2O), 2955, 2868, 1451, 1297, 1251, 1228, 1160, 1142, 1055, 929, 905, 837 cm^{-1}; ^{1}H NMR, δ=3.76 (d, *J*=2.0 Hz, 1H, 2-H), 3.62 (d, *J*=1.0 Hz, 1H, 3-H), 2.72 (ddd, *J*=12.7, 9.5, 1.7 Hz, 1H, 1-H), 2.12 (dd, *J*=13.5, 8.5 Hz, 1H, 4-H$_\beta$), 2.13–1.99 (complex signal, 2H, cyclopentyl C*H*), 1.96–1.82 (complex signal, 10H, cyclopentyl 2-H and 5-H, 4-H$_\alpha$, and 5-H$_\alpha$), 1.82–1.71 (complex signal, 5H, 4 cyclopentyl 3-H and 4-H, and 5-H$_\beta$), 1.69–1.56 (complex signal, 4H, rest of cyclopentyl 3-H and 4-H); ^{13}C NMR, δ=58.9 (CH, s, C3), 58.0 (CH, d, $^3J_{C-P}$=5.1 Hz, C2), 38.8 (CH, d, $^1J_{C-P}$=58.9 Hz, C1), 37.0 (CH, d, $^1J_{C-P}$= 66.4 Hz) and 36.6 (CH, d, $^1J_{C-P}$=66.4 Hz) (diastereotopic cyclopentyl CH), 27.15 (CH_2), 27.05 (2CH_2) and 26.96 (CH_2), (diastereotopic cyclopentyl C2 and C5), 26.7 (CH_2, s, C4), 26.4 (CH_2, d, $^3J_{C-P}$=9.3 Hz), 26.3 (CH_2, d, $^3J_{C-P}$= 9.8 Hz), 26.05 (CH_2, d, $^3J_{C-P}$=9.1 Hz) and 26.02 (CH_2, d, $^3J_{C-P}$=9.9 Hz) (diastereotopic cyclopentyl C3 and C4), 20.8 (CH_2, s, C5); ^{31}P NMR, δ=55.0; MS (EI), *m/z* (%): 268 (M$^{\cdot+}$, 5), 227 (21), 200 [(M−C_5H_8)$^{\cdot+}$, 13], 186 (20), 185 [(M−C_5H_7O)$^+$, 38], 145 (30), 119 (41), 118 [(C_5H_9)$POH_2^{\cdot+}$, 37], 99 (37), 83 ($C_5H_7O^+$, 37), 69 ($C_5H_9^+$, 53), 67 ($C_5H_7^+$, 100). Anal. calcd for $C_{15}H_{25}O_2P$: C, 67.14; H, 9.39. Found: C, 67.04; H, 9.23. The analytical sample of **5d** was obtained by crystallization (hexane) as a white hygroscopic solid, that easily became a wax. IR (KBr), ν_{max}: 3408 (OH st, H_2O), 2954, 2868, 1451, 1165, 1145, 934, 850 cm^{-1}; ^{1}H NMR, δ=3.66 (d, *J*=2.5 Hz, 1H, 2-H), 3.50 (d, *J*=2.2 Hz, 1H, 3-H), 2.31 (ddd, *J*=14.5, 10.6, 8.3 Hz, 1H, 1-H), 2.11 (dd, *J*=13.5, 8.0 Hz, 1H, 4-H$_\alpha$), 2.22–2.14 (m, 1H) and 2.12–2.05 (m, 1H) (diastereotopic cyclopentyl C*H*), 2.05–1.78 (complex signal, 8H, diastereotopic cyclopentyl 2-H and 5-H), 1.78–1.66 (complex signal, 5H, 4 diastereotopic cyclopentyl 3-H and 4-H, and 5-H$_\beta$), 1.65–1.54 (complex signal, 5H, 4 diastereotopic cyclopentyl 3-H and 4-H, and 4-H$_\beta$), 1.53–1.42 (m, 1H, 5-H$_\alpha$); ^{13}C NMR, δ=56.7 (CH, d, $^3J_{C-P}$=10.9 Hz, C3), 56.2 (CH, s, C2), 39.9 (CH, d, $^1J_{C-P}$=64.7 Hz, C1), 37.1 (CH, d, $^1J_{C-P}$=66.4 Hz) and 36.5 (CH, d, $^1J_{C-P}$=66.6 Hz) (diastereotopic cyclopentyl CH), 27.3 (CH_2, d, $^3J_{C-P}$= 10.3 Hz, C4), 27.2 (CH_2, broad signal) and 26.8 (CH_2, broad signal) (diastereotopic cyclopentyl C2 and C5), 26.7 (CH_2, d, $^3J_{C-P}$=8.9 Hz), 26.5 (CH_2, d, $^3J_{C-P}$=8.5 Hz), 26.0 (CH_2, d, $^3J_{C-P}$=9.3 Hz) and 25.9 (CH_2, d, $^3J_{C-P}$=9.7 Hz) (diastereotopic cyclopentyl C3 and C4), 20.3 (CH_2, s, C5); ^{31}P NMR, δ=53.6; MS (EI), *m/z* (%): 269 (2), 268 (M$^{\cdot+}$, 3), 186 (8), 185 [(M−C_5H_7O)$^+$, 9], 134 (28), 69 ($C_5H_9^+$, 20), 67 ($C_5H_7^+$, 100). Anal. calcd for $C_{15}H_{25}O_2P\cdot1/2H_2O$: C, 64.96; H, 9.45. Found: C, 65.02; H, 9.69.

3.1.9. 3-(Diphenylphosphinoyl)-2-cyclopentenol (7a). To a mixture of **2a** and **5a** (4.25 g, 15 mmol) in ethanol (150 mL) was added a solution of KOH in ethanol (18.7 mL, 1.6 M, 30 mmol) and the mixture was stirred at room temperature for 18 h. Then the solution was evaporated at reduced pressure to give a residue which was dissolved in H_2O (75 mL). The solution was made acidic (pH=1) with 5N HCl (10 mL) and was extracted with CH_2Cl_2 (3×60 mL). The combined organic extracts were dried (Na_2SO_4), filtered and concentrated in vacuo to give **7a** (4.21 g, 99% yield) as a pale yellow foamy solid. The analytical sample of **7a** was obtained as a white solid by crystallization (ethyl acetate), mp 110–111°C. IR (KBr), ν_{max}: 3338, 1604, 1438, 1333, 1175, 1107, 1086, 1027, 756, 724, 701 cm^{-1}; ^{1}H NMR, δ=7.69–7.62 (complex signal, 4H, diastereotopic Ar-H$_{ortho}$), 7.52–7.48 (complex signal, 2H, diastereotopic Ar-H$_{para}$), 7.44–7.40 (complex signal, 4H, diastereotopic Ar-H$_{meta}$), 6.34 (dq, *J*=10.2, 2.0 Hz, 1H, 2-H), 4.97–4.93 (m, 1H, 1-H), 3.60–3.15 (broad signal, 1H, OH), 2.70–2.63 (m, 1H, 4-H$_\beta$), 2.48–2.34 (complex signal, 2H, 4-H$_\alpha$ and 5-H$_\beta$), 1.84 (ddt, *J*=13.5, 8.5, 5.5 Hz, 1H, 5-H$_\alpha$); ^{13}C NMR, δ=150.0 (CH, d, $^2J_{C-P}$=9.6 Hz, C2), 138.9 (C, d, $^1J_{C-P}$=100.3 Hz, C3), 131.9 (CH, d, $^4J_{C-P}$=2.0 Hz, 2Ar-CH$_{para}$), 131.3 (CH, d, $^2J_{C-P}$=10.2 Hz, 4Ar-CH$_{ortho}$), 131.1 (C, d, $^1J_{C-P}$= 105.3 Hz) and 130.9 (C, d, $^1J_{C-P}$=104.8 Hz) (diastereotopic Ar-C$_{ipso}$), 128.5 (CH, d, $^3J_{C-P}$=12.1 Hz) and 128.4 (CH, d, $^3J_{C-P}$=12.2 Hz) (diastereotopic Ar-CH$_{meta}$), 77.3 (CH, d, $^3J_{C-P}$=18.2 Hz, C1), 34.2 (CH_2, d, $^3J_{C-P}$=8.1 Hz, C5), 31.8 (CH_2, d, $^2J_{C-P}$=10.6 Hz, C4); ^{31}P NMR, δ=24.5; MS (EI), *m/z* (%): 284 (M$^{\cdot+}$, 33), 267 [(M−OH)$^+$, 30], 256 (38), 255 (48), 202 (45), 201 [$PO(C_6H_5)_2^+$, 89], 183 (43), 125

[$HPO(C_6H_5)^+$, 22], 77 ($C_6H_5^+$, 100), 51 (96). Anal. calcd for $C_{17}H_{17}O_2P$: C, 71.82; H, 6.03. Found: C, 71.78; H, 6.07.

3.1.10. 3-(Dicyclohexylphosphinoyl)-2-cyclopentenol (7b). (a) From **5b**. To a solution of **5b** (300 mg, 1.01 mmol) in ethanol (6 mL) was added a solution of KOH in ethanol (1.2 mL, 1.6 M, 1.92 mmol) and the mixture was stirred at room temperature for 18 h. Then the solution was evaporated at reduced pressure to give a residue which was dissolved in H_2O (15 mL). The solution was made acidic (pH=1) with 2N HCl (2.2 mL) and was extracted with CH_2Cl_2 (3×50 mL). The combined organic phases were dried (Na_2SO_4), filtered and concentrated in vacuo to give **7b** (290 mg, 98% yield). The analytical sample of **7b** was obtained as a white solid by crystallization (ethyl acetate), mp 152.5–154°C. IR (KBr), ν_{max}: 3209, 2932, 2847, 1447, 1151, 1097, 1066, 1029, 876, 854, 821, 755, 730 cm^{-1}; ^1H NMR, δ=6.60 (dq, J=8.5, 2.0 Hz, 1H, 2-H), 4.94 (m, 1H, 1-H), 3.6–3.1 (broad s, 1H, OH), 2.63–2.54 (m, 1H, 4-H_β), 2.39–2.31 (complex signal, 2H, 4-H_α and 5-H_β), 1.98–1.91 (complex signal, 2H, 5-H_α and cyclohexyl C*H*), 1.86–1.60 (complex signal, 11H) and 1.44–1.13 (complex signal, 10H) (rest of cyclohexyl H); ^{13}C NMR, δ=150.5 (CH, d, $^2J_{C-P}$=5.1 Hz, C2), 136.8 (C, d, $^1J_{C-P}$=81.1 Hz, C3), 76.9 (CH, d, $^3J_{C-P}$=15.0 Hz, C1), 35.1 (CH_2, d, $^1J_{C-P}$=68.1 Hz,) and 34.8 (CH, d, $^1J_{C-P}$=68.4 Hz) (diastereotopic cyclohexyl CH), 34.2 (CH_2, d, $^3J_{C-P}$=6.5 Hz, C5), 33.1 (CH_2, d, $^2J_{C-P}$=9.5 Hz, C4), 26.6 (CH_2, broad s), 26.41 (CH_2, broad s), 26.38 (CH_2, broad s), 26.2 (CH_2, d, J_{C-P}=3.9 Hz), 25.9 ($2CH_2$, broad s), 25.5 ($2CH_2$, broad s), 24.65 (CH_2, d, J_{C-P}=3.4 Hz), 24.6 (CH_2, d, J_{C-P}=3.4 Hz) (cyclohexyl CH_2); ^{31}P NMR, δ=43.3; MS (EI), *m/z* (%): 296 (M^+, 1), 278 [$(M-H_2O)^{\cdot+}$, 4], 252 [$(M-C_2H_4O)^{\cdot+}$, 16], 214 [$(M-C_6H_{10})^{\cdot+}$, 17], 196 [$(M-C_6H_{10}-H_2O)^{\cdot+}$, 28], 170 [$(M-C_6H_{10}-C_2H_4O)^{\cdot+}$, 94], 114 [$(M-2C_6H_{10}-H_2O)^{\cdot+}$, 18], 113 (20), 83 ($C_6H_{11}^+$, 39), 67 ($C_5H_7^+$, 49), 55 (100). Anal. calcd for $C_{17}H_{29}O_2P$: C, 68.89; H, 9.87. Found: C, 68.78; H, 9.84.

(b) From **2b**. To a solution of *n*-buthyllithium (1 mL, 1.6 M in hexanes, 1.6 mmol) in THF (1 mL) at −78°C, was added dropwise a solution of **2b** (296 mg, 1.0 mmol) in anhydrous THF (3 mL). After 3 h at room temperature the mixture was heated under reflux for 15 h. The mixture was allowed to cool to room temperature, saturated aqueous solution of NH_4Cl (4 mL) was added, and the THF was evaporated under reduced pressure. The residue was diluted with water (10 mL) and extracted with ethyl acetate (3× 20 mL). The combined organic phases were dried (Na_2SO_4) and concentrated in vacuo to give a red oil (330 mg). Standard column chromatography [silica gel (30 g), ethyl acetate/methanol mixtures] of the above product gave **7b** (80 mg, 27% yield) as a white solid.

3.1.11. 3-(Diisopropylphosphinoyl)-2-cyclopentenol (7c). (a) From **2c**. To a solution of **2c** (324 mg, 1.5 mmol) in ethanol (6 mL) was added a solution of KOH in ethanol (2 mL, 1.6 M, 3.2 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 (15 mL). The solution was made acidic (pH=1) with 2N HCl (3 mL) and was extracted with CH_2Cl_2 (3×50 mL). The combined organic phases were dried (Na_2SO_4), filtered and concentrated in vacuo to give **7c** (71 mg). The aqueous phase was evaporated in vacuo to dryness and the residue was extracted with ethyl acetate (50 mL). The organic phase was dried (Na_2SO_4), filtered and concentrated in vacuo to give more **7c** (249 mg, 98% global yield). The analytical sample of **7c** was obtained as a colorless oil, by standard column chromatography [silica gel (25 g), ethyl acetate/ methanol mixtures]. IR (KBr), ν_{max}: 3281, 2964, 2935, 2874, 1465, 1326, 1263, 1172, 1146, 1095, 882, 695, 659 cm^{-1}; ^1H NMR, δ=6.64 (dq, J=8.5, 2.0 Hz, 1H, 2-H), 4.94 (m, 1H, 1-H), 4.0–3.4 (broad s, 1H, OH), 2.64–2.56 (m, 1H, 4-H_β), 2.39–2.31 (complex signal, 2H, 4-H_α and 5-H_β), 2.09–1.97 (complex signal, 2H, diastereotopic C*H*$(CH_3)_2$], 1.87–1.78 (m, 1H, 5-H_α), 1.19 (dd, J=15.0, 7.0 Hz, 3H), 1.17 (dd, J=14.5, 7.5 Hz, 3H), 1.10 (dd, J=14.5, 7.0 Hz, 3H), 1.07 (dd, J=15.0, 7.5 Hz, 3H) [diastereotopic CH(C*H*$_3)_2$]; ^{13}C NMR, δ=150.5 (CH, d, $^2J_{C-P}$=5.6 Hz, C2), 136.3 (C, d, $^1J_{C-P}$=81.4 Hz, C3), 76.8 (CH, d, $^3J_{C-P}$=15.4 Hz, C1), 34.2 (CH_2, d, $^3J_{C-P}$=6.5 Hz, C5), 33.2 (CH_2, d, $^2J_{C-P}$=9.3 Hz, C4), 25.1 (CH, d, $^1J_{C-P}$= 68.5 Hz) and 24.7 (CH, d, $^1J_{C-P}$=67.9 Hz) [diastereotopic *C*H$(CH_3)_2$], 15.9 (CH_3, broad s) and 14.9 (CH_3, broad s) [diastereotopic *C*H$(CH_3)_2$]; ^{31}P NMR, δ=50.5; MS (EI), *m/z* (%): 216 ($M^{\cdot+}$, 44), 199 [$(M-OH)^+$, 59], 174 (94), 173 [$(M-C_3H_7)^+$, 88], 156 [$(M-C_3H_6-H_2O)^{\cdot+}$, 49], 131 [$(M-C_3H_7-C_3H_6)^+$, 43], 114 [$(C_5H_5POH_2)^{\cdot+}$, 29], 113 [$(M-C_3H_7-C_3H_6-H_2O)^+$, 65], 92 [$C_3H_7POH_2^{\cdot+}$, 15), 83 ($C_5H_7O^+$, 85), 67 ($C_5H_7^+$, 100). Anal. calcd for $C_{11}H_{21}O_2P{\cdot}1.8H_2O$: C, 53.12; H, 9.98. Found: C, 52.97; H, 9.68.

(b) From **5c**. Starting from **5c** (340 mg, 1.57 mmol) and following the above described procedure, **7c** (324 mg, 95% yield) was obtained.

3.1.12. 3-(Dicyclopentylphosphinoyl)-2-cyclopentenol (7d). To a mixture of **2d** and **5d** (100 mg, 0.37 mmol) in ethanol (5 mL) was added a solution of KOH in ethanol (0.46 mL, 1.6 M, 0.74 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 (5 mL). The solution was made acidic (pH=1) with 2N HCl (2 mL) and was extracted with CH_2Cl_2 (3×10 mL). The combined organic phases were dried (Na_2SO_4), filtered and concentrated in vacuo to give **7d** (76 mg, 76% yield) as a yellowish oil. IR (NaCl), ν_{max}: 3294, 2955, 2887, 1450, 1327, 1259, 1153, 1098, 1062, 1026, 907 cm^{-1}; ^1H NMR, δ=6.63 (dq, J=9.0, 2.0 Hz, 1H, 2-H), 4.90 (m, 1H, 1-H), 3.45 (broad s, 1H, OH), 2.61–2.53 (m, 1H, 4-H_β), 2.35–2.27 (complex signal, 2H, 4-H_α and 5-H_β), 2.10–1.97 (complex signal, 2H, diastereotopic cyclopentyl CH), 1.88–1.49 (complex signal, 17H, cyclopentyl CH_2 and 5-H_α); ^{13}C NMR, δ=149.3 (CH, d, $^2J_{C-P}$=5.7 Hz, C2), 138.1 (C, d, $^1J_{C-P}$=85.4 Hz, C3), 76.8 (CH, d, $^3J_{C-P}$=15.3 Hz, C1), 36.9 (CH, d, $^1J_{C-P}$=71.7 Hz) and 36.5 (CH, d, $^1J_{C-P}$= 71.8 Hz) (diastereotopic cyclopentyl CH), 34.2 (CH_2, d, $^3J_{C-P}$=6.7 Hz, C5), 32.6 (CH_2, d, $^2J_{C-P}$=10.2 Hz, C4), 26.8–26.6 (CH_2) and 26.2–26.0 (CH_2) (cyclopentyl CH_2); ^{31}P NMR, δ=43.9; MS (EI), *m/z* (%): 268 (M^+, 1), 200 [$(M-C_5H_8)^{\cdot+}$, 11], 182 [$(M-C_5H_8-H_2O)^{\cdot+}$, 13], 156 (52), 83 ($C_5H_7O^+$, 32), 69 ($C_5H_9^+$, 49), 67 ($C_5H_7^+$, 100). Anal. calcd for $C_{15}H_{25}O_2P{\cdot}H_2O$: C, 62.92; H, 9.50. Found: C, 62.86; H, 9.15.

3.1.13. *c*-3-(Diphenylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol (8a). (a) From a mixture of **2a** and **5a**. To a cold solution (ice-bath) of **9** (388 mg, 1.80 mmol) in anhydrous THF (7.5 mL) was added dropwise *n*-butyllithium (1.76 mL, 1.6 M in hexanes, 2.82 mmol). The suspension was cooled to −78°C and a solution of a mixture of anhydrous epoxides **2a** and **5a** (500 mg, 1.76 mmol, azeotropic distillation of the water content with toluene in a Dean–Stark equipment) in THF (15 mL) was added dropwise. After 3 h at room temperature, the mixture was heated under reflux for 15 h. The mixture was allowed to cool to room temperature, saturated aqueous solution of NH_4Cl (15 mL) was added, and the organic phase was separated and evaporated to dryness in vacuo. The residue was taken in water (15 mL) and extracted with CH_2Cl_2 (3×15 mL). The combined organic phases were dried (Na_2SO_4) and concentrated in vacuo to give **8a** as a brown foamy solid (770 mg, 87% yield). The analytical sample of **8a** was obtained as a white solid by crystallization (ethyl acetate), mp 189.5–190°C. IR (KBr), ν_{max}: 3425, 3255, 1437, 1173, 1144, 1120, 1103, 765, 745, 722, 697 cm^{-1}; ^1H NMR, δ=7.86–7.81 (m, 2H, Ar-H_{ortho}), 7.73–7.68 (m, 2H, Ar-H_{ortho}), 7.64–7.37 (complex signal, 14H, 4Ar-H_{para}, 6Ar-H_{meta}, 4Ar-H_{ortho}), 7.32–7.28 (m, 2H, 2Ar-H_{meta}), 4.01 (dt, J=8.0, 6.5 Hz, 1H, 1-H), 3.24 (ddd, J=14.5, 8.2, 2.7 Hz, 1H, $CH_{syn}PO(C_6H_5)_2$), 2.94–2.86 (ddt, J=19.5, 6.5, 10.5 Hz, 1H, 3-H), 2.29–2.15 (complex signal, 2H, 2-H and $CH_{anti}PO(C_6H_5)_2$), 2.02–1.90 (complex signal, 2H, 4-H_β and 5-H_β), 1.83–1.73 (m, 1H, 4-H_α), 1.32–1.24 (m, 1H, 5-H_α); ^{13}C NMR, δ=133.15 and 133.07 [higher δ signals of 2 d, Ar-C_{ipso} of $CH_2PO(C_6H_5)_2$], 131.8 (CH, broad s, 2+2 diastereotopic Ar-CH_{para}), 131.8 [CH, d, $^2J_{C-P}$=9.1 Hz, Ar-CH_{ortho} of $CH_2PO(C_6H_5)_2$], 131.3 (CH, d, $^2J_{C-P}$=9.8 Hz) and 131.1 (CH, d, $^2J_{C-P}$=9.1 Hz) [2+2Ar–CH_{ortho} of 3-$PO(C_6H_5)_2$], 130.5 [lower δ signal of one d, Ar-C_{ipso} of 3-$PO(C_6H_5)_2$], 130.3 [CH, d, $^2J_{C-P}$=9.1 Hz, 2Ar-CH_{ortho} of $CH_2PO(C_6H_5)_2$], 130.0 (C, d, $^1J_{C-P}$=97.0 Hz, Ar-C_{ipso} of 3-$PO(C_6H_5)_2$), 128.8 (CH, d, $^3J_{C-P}$=12.2 Hz), 128.7 (CH, d, $^3J_{C-P}$=11.0 Hz), 128.6 (CH, d, $^3J_{C-P}$=12.1 Hz) and 128.4 (CH, d, $^3J_{C-P}$=11.6 Hz) (Ar-CH_{meta}), 78.7 (CH, dd, $^3J_{C-P}$=10.6, 2.7 Hz, C1), 43.5 (CH, s, C2), 41.7 (CH, dd, $^1J_{C-P}$=72.0 Hz, $^3J_{C-P}$=12.8 Hz, C3), 35.0 (CH_2, d, $^1J_{C-P}$=68.9 Hz, CH_2P), 32.5 (CH_2, d, $^3J_{C-P}$=4.3 Hz, C5), 23.3 (CH_2, s, C4); ^{31}P NMR, δ=38.3 [$CH_2PO(C_6H_5)_2$], 35.8 [3-$PO(C_6H_5)_2$]; MS (EI), *m/z* (%): 501 [$(M+H)^+$, 1], 299 [$[M-PO(C_6H_5)_2]^+$, 100], 202 (23), 201 [$PO(C_6H_5)_2^+$, 95], 77 ($C_6H_5^+$, 35). Anal. calcd for $C_{30}H_{30}O_3P_2 \cdot 1/2H_2O$ C, 70.72; H, 6.13. Found: C, 70.88; H, 6.36.

(b) From **7a**. To a cold (ice-bath) solution of **9** (78 mg, 0.35 mmol) in anhydrous THF (2 mL) was added dropwise *n*-butyllithium (0.35 mL, 1.6 M in hexanes, 0.56 mmol). The mixture was cooled to −78°C and a solution of anhydrous **7a**, obtained by dissolving **7a** (100 mg, 0.35 mmol) in toluene (5 mL) followed by distillation of most of the toluene (4 mL) at atmospheric pressure, was added dropwise. After 3 h at room temperature the mixture was heated under reflux for 15 h. Following the workup described before, **8a** (152 mg, 87% yield) was obtained as a brown foamy solid.

3.1.14. *c*-3-(Dicyclohexylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol (8b). (a) From **2b**. To a cold solution (ice-bath) of **9** (525 mg, 2.39 mmol) in anhydrous THF (7 mL) was added dropwise *n*-butyllithium (2.4 mL, 1.6 M in hexanes, 3.82 mmol). The suspension was cooled to −78°C and a solution of anhydrous **2b** (706 mg, 2.39 mmol, azeotropic distillation of the water content with toluene in a Dean–Stark equipment) in THF (3 mL) was added dropwise. After 3 h at room temperature the mixture was heated under reflux for 15 h. Then, it was allowed to cool to room temperature, saturated aqueous solution of NH_4Cl (10 mL) was added, and the mixture was evaporated to dryness in vacuo. The residue was taken in water (10 mL) and extracted with CH_2Cl_2 (3×10 mL). The combined organic phases were dried (Na_2SO_4) and concentrated in vacuo to give a yellow solid (1.18 g). Flash column chromatography [silica gel (60 g), ethyl acetate/methanol mixtures] gave **8b** as a white solid (900 mg, 74% yield) on elution with a mixture of ethyl acetate/methanol in the ratio of 97:3, and **7b** (100 mg, 14%), on elution with a mixture of ethyl acetate/methanol in the ratio of 96:4. The analytical sample of **8b** was obtained as a white solid by crystallization (ethyl acetate), mp 163–164.5°C; IR (KBr), ν_{max}: 3486, 3422, 3360, 3295, 2929, 2853, 1440, 1163, 1140, 1125, 750, 695 cm^{-1}; ^1H NMR, δ=8.03–7.95 (m, 2H), 7.74–7.72 (m, 2H) (Ar-H_{ortho}), 7.50–7.38 (complex signal, 6H, 4Ar-H_{meta} and 2Ar-H_{para}), 6.42 (broad s, 1H, OH), 3.96 (*pseudo* q, J=7.5 Hz, 1H, 1-H), 3.74 (dd, J=15.0, 7.0 Hz, 1H, $CH_{syn}PO(C_6H_5)_2$], 2.34–2.16 (complex signal, 2H, 2-H and 3-H), 2.10 (m, 1H, 5-H_β), 2.02 [*pseudo* dt, J=11.0, 15.0 Hz, 1H, $CH_{anti}PO(C_6H_5)_2$], 1.94 (broad d, J=12.5 Hz, 1H) and 1.86–1.57 (complex signal, 14H) (12 cyclohexyl H, 4-H_α, 4-H_β and 5-H_α), 1.43–0.98 (complex signal, 10H, rest of cyclohexyl H); ^{13}C NMR, δ=131.82 (CH, d, $^4J_{C-P}$=3.2 Hz) and 131.78 (CH, d, $^4J_{C-P}$=3.2 Hz) (Ar-CH_{para}), 132.8 (C, d, $^1J_{C-P}$=98.0 Hz) and 130.9 (C, $^1J_{C-P}$=98.0 Hz) (Ar-C_{ipso}), 131.6 (CH, d, $^2J_{C-P}$=9.7 Hz) and 130.4 (CH, d, $^2J_{C-P}$=9.3 Hz) (Ar-CH_{ortho}), 128.7 (CH, d, $^3J_{C-P}$=12.2 Hz) and 128.6 (CH, d, $^3J_{C-P}$=11.8 Hz) (Ar-CH_{meta}), 78.7 (CH, d, $^3J_{C-P}$=11.6 Hz, C1), 45.3 (CH, *pseudo* t, $^2J_{C-P}$=3.2 Hz, C2), 39.5 (CH, dd, $^1J_{C-P}$=60.1 Hz, $^3J_{C-P}$=14.2 Hz, C3), 34.8 (CH_2, d, $^1J_{C-P}$=68.8 Hz, $CH_2PO(C_6H_5)_2$], 35.5 (CH, d, $^1J_{C-P}$=62.8 Hz) and 34.6 (CH, d, $^1J_{C-P}$=61.9 Hz) (diastereotopic cyclohexyl CH), 32.7 (CH_2, d, $^3J_{C-P}$=6.0 Hz, C5), 26.7–25.1 (several CH_2, cyclohexyl CH_2), 22.5 (CH_2, s, C4); ^{31}P NMR, δ=37.4 [$PO(C_6H_5)_2$], 53.9 [$PO(C_6H_{11})_2$]; MS (EI), *m/z* (%): 513 [$(M+H)^+$, 1], 429 [$(M-C_6H_{11})^+$, 2], 347 [$(M-C_6H_{10}-C_6H_{11})^+$, 11], 311 (8), 299 [$(M-C_{12}H_{22}PO)^+$, 100], 281 [$(M-C_{12}H_{22}PO-H_2O)^+$, 9], 201 [$PO(C_6H_5)_2^+$, 46]. Anal. calcd for $C_{30}H_{42}O_3P_2$: C, 70.29; H, 8.26. Found: C, 70.28; H, 8.31.

(b) From **7b**. To a cold (ice-bath) solution of **9** (78 mg, 0.35 mmol) in anhydrous THF (3 mL) was added dropwise *n*-butyllithium (0.35 mL, 1.6 M in hexanes, 0.56 mmol). The mixture was cooled to −78°C and a solution of anhydrous **7b**, obtained by dissolving **7b** (104 mg, 0.35 mmol) in toluene (5 mL) followed by distillation of most of the toluene (4 mL) at atmospheric pressure, was added dropwise. After 3 h at room temperature the mixture was heated under reflux for 15 h. Following the workup described before, a mixture of **8b** (main component) and **7b** (minor component) in an approximate ratio of 97:3 (^1H NMR), was quantitatively obtained.

Table 3. Experimental data of the X-ray crystal-structure determination of compounds **2a**, **8b**–**8d**[18]

Compound	**2a**	**8b**	**8c**	**8d**
Molecular formula	$C_{34}H_{34}O_4P_2$	$C_{30}H_{44}O_4P_2$	$C_{24}H_{36}O_4P_2$	$C_{28}H_{40}O_4P_2$
Molecular mass	568.55	530.63	450.47	502.54
Crystal system	Monoclinic	Monoclinic	Monoclinic	Monoclinic
Space group	$P2_1/n$	$P2_1/n$	$P2_1/a$	$P2_1/n$
Cell parameters	[a]	[a]	[a]	[b]
A (Å)	14.222(6)	25.423(3)	12.08(2)	13.7110(10)
b (Å)	14.190(5)	9.717(2)	18.40(2)	9.5540(10)
c (Å)	14.726(6)	26.381(2)	12.250(10)	20.8330(10)
β (°)	96.26(3)	117.63(6)	119.04(9)	96.0740(10)
V (Å^3)	2954(2)	5773(14)	2380(5)	2713.7(4)
Z	4	8	4	4
F(000)	1200	2288	968	1080
D(calcd) (mg m^{-3})	1.278	1.220	1.257	1.230
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 reflect.	8869	17210	4429	12004
Independent reflect.	8527	16786	4209	5898
Observed reflect.	3387	16686	3399	4040
μ(Mo Kα)[a] (mm^{-1})	0.184	0.187	0.210	0.191
R	0.037	0.037	0.056	0.030
Rw	0.065	0.078	0.149	0.080
$\Delta\rho_{max}$[b] (e Å^{-3})	0.683	0.572	0.589	0.271
$\Delta\rho_{mim}$[c] (e Å^{-3})	−0.199	−0.336	−0.566	−0.165
Refined parameters	473	651	274	443
Max. shift/e.s.d.	0.00	0.00	0.00	0.00

[a] Determined by automatic centering of 25 reflections ($12<\theta<21°$). [b] Determined by automatic centering of 9418 reflections ($3<\theta<30°$).
[a] μ(Mo Kα) linear absorption coefficient. Radiation Mo Kα (λ=0.71069 Å).
[b] Maximum peaks in final difference synthesis.
[c] Minimum peaks in final difference synthesis.

3.1.15. *c*-3-(Diisopropylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol (8c). (a) From **2c**. To a cold (ice-bath) solution of **9** (220 mg, 1.0 mmol) in anhydrous THF (3 mL) was added dropwise *n*-butyllithium (1.0 mL, 1.6 M in hexanes, 1.6 mmol). The suspension was cooled to −78°C and a solution of **2c**, obtained by dissolving **2c** (216 mg, 1.0 mmol) in toluene (5 mL) followed by distillation of most of the solvent (4 mL) at atmospheric pressure, was added dropwise. After 3 h at room temperature the mixture was heated under reflux for 15 h. Then, it was allowed to cool to room temperature, saturated aqueous solution of NH_4Cl (4 mL) was added and the mixture was evaporated to dryness in vacuo. The residue was taken in water (10 mL) and extracted with CH_2Cl_2 (3×10 mL). The combined organic phases were dried (Na_2SO_4) and concentrated in vacuo to give a brown oil (340 mg). Flash column chromatography [silica gel (19 g), ethyl acetate/methanol mixtures] gave **8b** as a white solid (290 mg, 67% yield) on elution with a mixture ethyl acetate/methanol in the ratio of 96:4. The analytical sample was obtained as a white solid by crystallization (ethyl acetate), mp 126–128°C; IR (KBr), ν_{max}: 3410, 3218, 2962, 2878, 1466, 1438, 1170, 1154, 1123, 1098, 793, 759, 745 cm^{-1}; ^{1}H NMR, δ=8.05–8.00 (m, 2H) and 7.75–7.70 (m, 2H) (Ar-H$_{ortho}$), 7.50–7.44 (complex signal, 4H) and 7.42–7.38 (m, 2H) (Ar-H$_{meta}$ and Ar-H$_{para}$), 6.8–6.0 (broad s, 1H, OH), 3.98 (*pseudo* q, J=8.0 Hz, 1H, 1-H), 3.74 (ddd, J=15.0, 7.0, 2.0 Hz, 1H, CH$_{syn}$PO(C$_6$H$_5$)$_2$), 2.27 (m, 1H, 2-H), 2.21 (ddt, J=13.5, 8.0, 11.0 Hz, 1H, 3-H), 2.11 (m, 1H, 5-H$_\beta$), 2.08–1.95 (complex signal, 3H, diastereotopic C*H*(CH$_3$)$_2$ and CH$_{anti}$PO(C$_6$H$_5$)$_2$), 1.87–1.75 (m, 1H, 4-H$_\beta$), 1.75–1.60 (complex signal, 2H, 4-H$_\alpha$ and 5-H$_\alpha$), 1.19 (dd, J=14.0, 7.0 Hz, 3H), 1.10 (dd, J=14.5, 7.0 Hz, 3H), 1.09 (dd, J=15.0, 7.5 Hz, 3H), 1.06 (dd, J=15.0, 7.5 Hz, 3H) [diastereotopic CH(C*H*$_3$)$_2$]; ^{13}C NMR, δ=132.9 (C, d, $^1J_{C-P}$=101.0 Hz) and 130.1 (C, signal of overlapped d) (Ar-C$_{ipso}$), 131.7 (CH, broad s) (Ar-CH$_{para}$), 131.4 (CH, d, $^2J_{C-P}$=9.8 Hz) and 130.3 (CH, d, $^2J_{C-P}$=9.8 Hz) (Ar-CH$_{ortho}$), 128.68 (CH, d, $^3J_{C-P}$=11.7 Hz) and 128.55 (CH, d, $^3J_{C-P}$=11.1 Hz) (Ar-CH$_{meta}$), 78.6 (CH, d, $^3J_{C-P}$=11.6 Hz, C1), 45.2 (CH, s, C2), 39.3 (CH, dd, $^1J_{C-P}$=59.9 Hz, $^3J_{C-P}$=14.2 Hz, C3), 34.8 (CH$_2$, d, $^1J_{C-P}$=68.7 Hz, *C*H$_2$PO(C$_6$H$_5$)$_2$), 32.8 (CH$_2$, d, $^3J_{C-P}$=5.6 Hz, C5), 25.3 (CH$_2$, d, $^1J_{C-P}$=62.6 Hz) and 23.8 (CH, d, $^1J_{C-P}$=62.0 Hz) [diastereotopic *C*H(CH$_3$)$_2$], 22.9 (CH$_2$, broad s, C4), 16.8 (CH$_3$, d, $^2J_{C-P}$=3.3 Hz), 16.6 (CH$_3$, broad s), 15.9 (CH$_3$, broad s), 15.4 (CH$_3$, broad s) diastereotopic CH(*C*H$_3$)$_2$]; ^{31}P NMR, δ=33.1 [PO(C$_6$H$_5$)$_2$], 55.1 [PO(*i*-Pr)$_2$]; MS (EI), *m/z* (%): 433 (1), 432 (M$^{\cdot+}$, 0.5), 347 ((M−C$_3$H$_6$–C$_3$H$_7$)$^+$, 6], 299 [(M−C$_6$H$_{14}$PO)$^+$, 100], 231 [(M−PO(C$_6$H$_5$)$_2$)$^+$, 11], 201 [PO(C$_6$H$_5$)$_2^+$, 36]. Anal. calcd for $C_{24}H_{34}O_3P_2{\cdot}H_2O$: C, 63.98; H, 8.06. Found: C, 64.25; H 7.82.

(b) From **5c**. Starting from **9** (190 mg, 0.85 mmol), *n*-butyllithium (0.85 mL, 1.6 M in hexanes, 1.36 mmol) and **5c** (183 mg, 0.85 mmol) and following the above described procedure under (a), **8c** (340 mg, 92% yield) was obtained.

(c) From **7c**. Starting from **9** (166 mg, 0.75 mmol), *n*-butyllithium (0.75 mL, 1.6 M in hexanes, 1.2 mmol) and **7c** (162 mg, 0.75 mmol) and following the above described procedure under (a), **8c** (180 mg, 56% yield) was obtained.

3.1.16. *c*-3-(Dicyclopentylphosphinoyl)-*t*-2-[(diphenylphosphinoyl)methyl]-*r*-1-cyclopentanol (8d). (a) From a mixture of **2d** and **5d**. To a cold (ice-bath) solution of **9** (403 mg, 1.86 mmol) in anhydrous THF (5 mL) was added dropwise *n*-butyllithium (1.86 mL, 1.6 M in hexanes, 2.98 mmol). The suspension was cooled to −78°C and a

solution of a mixture of anhydrous **2d** and **5d** (500 mg, 1.86 mmol, azeotropic distillation of the water content with toluene in a Dean–Stark equipment) in THF (15 mL) was added dropwise. After 3 h at room temperature the mixture was heated under reflux for 15 h. The mixture was allowed to cool to room temperature, saturated aqueous solution of NH_4Cl (8 mL) was added, and the organic phase was separated and evaporated to dryness in vacuo. The residue was taken in water (8 mL) and extracted with CH_2Cl_2 (3×20 mL). The combined organic phases were dried (anhydrous Na_2SO_4) and concentrated in vacuo to give **8d** as a brown foamy solid (854 mg, 95%). The analytical sample of **8d** was obtained as a pale yellow solid by crystallization (AcOEt/hexane in the ratio of 10:1), mp 179–180°C. IR (KBr), ν_{max}: 3430, 3308, 2955, 2865, 1436, 1172, 1149, 1121, 1104, 804, 758, 722, 697 cm^{-1}; ^1H NMR, δ=8.00–7.95 (m, 2H) and 7.75–7.70 (m, 2H) (Ar-H_{ortho}), 7.48–7.43 (complex signal, 4H) and 7.41–7.37 (m, 2H) (Ar-H_{meta} and Ar-H_{para}), 6.40 (broad s, 1H, OH), 3.97 (*pseudo* q, J=7.5 Hz, 1H, 1-H), 3.78 (ddd, J=15.0, 6.0, 1.0 Hz, 1H, $CH_{syn}PO(C_6H_5)_2$), 2.28–2.03 (complex signal, 4H, 2-H, 3-H, 5-H_β, $CH_{anti}PO(C_6H_5)_2$], 1.96–1.30 (complex signal, 21H, cyclopentyl H, 4-H_α, 4-H_β and 5-H_α); ^{13}C NMR, δ=132.8 (C, d, $^1J_{C-P}$=101.3 Hz) and 130.7 (C, d, $^1J_{C-P}$=98.5 Hz) (diastereotopic Ar-C_{ipso}), 131.8 (CH, broad s) and 131.7 (CH, broad s) (diastereotopic Ar-CH_{para}), 131.6 (CH, d, $^2J_{C-P}$=10.0 Hz) and 130.4 (CH, d, $^2J_{C-P}$=9.1 Hz) (diastereotopic Ar-CH_{ortho}), 128.6 (CH, d, $^3J_{C-P}$=12.1 Hz, Ar-CH_{meta}), 78.7 (CH, d, $^3J_{C-P}$=12.3 Hz, C1), 44.9 (CH, s, C2), 41.6 (CH, dd, $^1J_{C-P}$=63.7 Hz, $^3J_{C-P}$=14.5 Hz, C3), 36.8 (CH, d, $^1J_{C-P}$=66.1 Hz) and 35.1 (CH, d, $^1J_{C-P}$=65.9 Hz) (diastereotopic cyclopentyl CH), 34.7 (CH_2, d, $^1J_{C-P}$=68.9 Hz, $CH_2PO(C_6H_5)_2$), 32.5 (CH_2, d, $^3J_{C-P}$=6.4 Hz, C5), 27.7 (CH_2, s), 27.0 ($2CH_2$, s) and 25.9 (CH_2, s) (diastereotopic cyclopentyl C2 and C5), 26.6 (CH_2, d, $^3J_{C-P}$=8.9 Hz), 25.8–25.9 ($2CH_2$, d) and 25.7 (CH_2, d, $^3J_{C-P}$=9.9 Hz) (diastereotopic cyclopentyl C3 and C4), 22.6 (CH_2, s, C4); ^{31}P NMR, δ=36.8 [$PO(C_6H_5)_2$], 55.4 [$(PO(C_5H_9)_2$]; MS (EI), *m/z* (%): 485 [$(M+H)^+$, 2], 299 [$M-PO(C_5H_9)_2^+$, 100], 283 [$M-[PO(C_6H_5)_2]^+$, 14], 201 [$PO(C_6H_5)_2^+$, 39], 69 ($C_5H_9^+$, 13), 67 ($C_5H_7^+$, 15). Anal. calcd for $C_{28}H_{38}O_3P_2$: C, 69.41; H, 7.90. Found: C, 69.48; H, 7.95.

(b) From **7d**. Starting from **9** (93 mg, 0.43 mmol), *n*-butyllithium (0.35 mL, 1.6 M in hexanes, 0.56 mmol) and **7d** (93 mg, 0.35 mmol) and following the above described procedure under (a), **8d** (152 mg, 90% yield) was obtained.

3.2. X-Ray crystal-structure determinations of 2a, 8b–8d (Table 3)

A prismatic crystal was selected and mounted on an MAR345 (**8d**) or on an Enraf-Nonius CAD4 four-cicle diffractometer (**2a**, **8b** and **8c**). 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. Reflections were measured in the range $2.00\leq\theta\leq29.97$ and were assumed as observed by 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 SHELXS computer program[19] and refined by full-matrix least-squares method with SHELX93[20] (for **8b** and **8c**) or SHELX97[21] (for **2a** and **8d**) computer programs. The function minimized was $\sum w[|F_o|^2-|F_c|^2]^2$, where $w=[\sigma^2(I)+(0.0269P)^2]^{-1}$ for **2a**, $w=[\sigma^2(I)+(0.0365P)^2]^{-1}$ for **8b**, $w=[\sigma^2(I)+(0.0926P)^2]^{-1}$ for **8c** and $w=[\sigma^2(I)+(0.0551P)^2]^{-1}$ for **8d**, being $P=(|F_o|^2-2|F_c|^2)/3$ in all cases; f, f' and f'' were taken from International Tables of X-ray Crystallography.[22] The position of the hydrogen atoms for **8b**–**8d** were computed and refined with an overall isotropic temperature factor, using a riding model. For **2a**, 28 hydrogen atoms were located from a difference synthesis and refined with an overall isotropic temperature factor and six hydrogen atoms were computed and refined with an overall isotropic temperature factor equals to 1.2 time the equivalent isotropic temperature factor of the atom to which are linked and using a riding model.

Acknowledgements

Financial support from the Dirección General de Investigación of Ministerio de Ciencia y Tecnología (project QUI1999-0512) and a fellowship from the Generalitat de Catalunya (to G. C.) are gratefully acknowledged. We thank the Serveis Científico-Tècnics of the University of Barcelona and particularly Dr M. Feliz and Dr A. Linares for recording the NMR spectra, and Ms P. Domènech from the Centro de Investigación y Desarrollo (C.I.D.) (Barcelona, Spain) for carrying out the elemental analyses.

References

1. (a) Noyori, R. *Asymmetric Catalysis in Organic Synthesis*; Wiley: New York, 1994. (b) Ojima, I. *Catalytic Asymmetric Synthesis*; 2nd ed; Wiley-VCH: Weinheim, 2000. (c) *Methods of Organic Synthesis, Houben-Weyl: Stereoselective Synthesis*, Helmchen, G., Hoffmann, R. W., Mulzer, J., Schaumann, E., Eds.; Georg Thieme: New York, 1996. (d) Jacobsen, E. N.; Pfalz, A.; Yamamoto, H. *Comprehensive Asymmetric Catalysis I–III*; Springer: Berlin, 1999. (e) Noyori, R.; Ohkuma, T. *Angew. Chem. Int. Ed. Engl.* **2001**, *40*, 40–73.
2. (a) Collins, A. N.; Sheldrake, G. N.; Crosby, J. *Chirality in Industry I*; Wiley: Chischester, 1992. (b) Collins, A. N.; Sheldrake, G. N.; Crosby, J. *Chirality in Industry II*; Wiley: Chischester, 1997. (c) Sheldon, R. A. *Chirotechnology*; Marcel Dekker: New York, 1993.
3. Clayden, J.; Warren, S. *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 241–270.
4. **3a** had been prepared by reaction of diphenylphosphide anion with 3-chlorocyclopentene. Haynes, R. K.; Katsifis, A. G.; Vonwiller, S. C.; Hambley, T. W. *J. Am. Chem. Soc.* **1988**, *110*, 5423–5433.
5. For the epoxidation of β,γ-unsaturated phosphine oxides with *m*-CPBA, see: (a) Symmes, Jr., C.; Quin, L. D. *Tetrahedron Lett.* **1976**, 1853–1856. (b) Clayden, J.; Collington, E. W.; Egert, E.; McElroy, A. B.; Warren, S. *J. Chem. Soc., Perkin*

Trans. 1 **1994**, 2801–2810. (c). Yamashita, M.; Yabui, A.; Oshikawa, T.; Hanaya, T.; Yamamoto, H. *Heterocycles* **1994**, *38*, 1449–1452. (d) Currie, M.; Suckling, C. J.; Zhu, L.; Irvine, J.; Stimson, W. H. *Tetrahedron* **1995**, *51*, 8915–8922.

6. Precedents of this rearrangement are known: (a) Arbuzov, B. A.; Rakov, A. P.; Vizel, A. O. *Bull. Acad. Sci. USSR, Div. Chem. Sci. (Engl. Transl.)* **1970**, *10*, 78–82. (b) Bodalski, R.; Janecki, T.; Galdecki, Z.; Glowka, M. *Phosphorus Sulfur Relat. Elem.* **1982**, *14*, 15–21. (c) Quin, L. D.; Lawson, H. F. *Phosphorus Sulfur Relat. Elem.* **1983**, *15*, 195–203. (d) Torr, R. S.; Warren, S. *J. Chem. Soc., Perkin Trans. 1* **1983**, 1169–1171. (e) Kato, M.; Nomura, S.; Kobayashi, H.; Miwa, T. *Chem. Lett.* **1986**, 281–284. (f) Clayden, J.; McElroy, A. B.; Warren, S. *J. Chem. Soc., Perkin Trans. 1* **1995**, 1913–1934.
7. Guéguen, C.; O'Brien, P.; Powell, H. R.; Raithby, P. R.; Warren, S. *J. Chem. Soc., Perkin Trans. 1* **1998**, 3405–3417.
8. Breitmaier, E.; Voelter, W. *Carbon-13 NMR Spectroscopy*; 3rd ed; VCH: Weinheim, 1990; p 413.
9. (a) Perlmutter, P. *Conjugate Addition Reactions in Organic Synthesis*; Pergamon: Oxford, 1992. (b) Rossiter, B. E.; Swingle, N. M. *Chem. Rev.* **1992**, *92*, 771–806.
10. Collins, D. J.; Mollard, S.-A.; Rose, N.; Swan, J. M. *Aust. J. Chem.* **1974**, *27*, 2365–2372.
11. Cavalla, D.; Cruse, W. B.; Warren, S. J. *J. Chem. Soc., Perkin Trans. 1* **1987**, 1883–1898.
12. (a) Pietrusiewicz, K. M.; Zablocka, M.; Monkiewicz, J. *J. Org. Chem.* **1984**, *49*, 1522–1526. (b) Afarinkia, K.; Binch, H. M.; Modi, C. *Tetrahedron Lett.* **1998**, *39*, 7419–7422.
13. Fleming, I.; Gil, S.; Sarkar, A. K.; Schmidlin, T. J. *Chem. Soc., Perkin Trans. 1* **1992**, 3351–3361.
14. Bartels, B.; Clayden, J.; González Martín, C.; Nelson, A.; Russell, M. G.; Warren, S. *J. Chem. Soc., Perkin Trans. 1* **1999**, 1807–1822.
15. Obtained by Swern oxidation of (±)-**7a**, followed by enantioselective reduction of the formed ketone with the borane/(*S*)-2-methyl-CBS–oxazaborolidine complex.
16. (a) MacNeil, P. A.; Roberts, N. K.; Bosnich, B. *J. Am. Chem. Soc.* **1981**, *103*, 2273–2280. (b) Inoguchi, K.; Achiwa, K. *Synlett* **1991**, 49–51. (c) Inoguchi, K.; Fujie, N.; Yoshikawa, K.; Achiwa, K. *Chem. Pharm. Bull.* **1992**, *40*, 2921–2926. (d) Pàmies, O.; Net, G.; Ruiz, A.; Claver, C. *Eur. J. Inorg. Chem.* **2000**, 2011–2016. See also, (e) Zabotina, E. Y.; de Kanter, F. J. J.; Bickelhaupt, F.; Wife, R. L. *Tetrahedron* **2001**, *57*, 10177–10180.
17. Roucoux, A.; Thieffry, L.; Carpentier, J.-F.; Devocelle, M.; Méliet, C.; Agbossou, F.; Mortreux, A. *Organometallics* **1996**, *15*, 2440–2449.
18. Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 177290 (**8b**), CCDC 177291 (**8c**), CCDC 177292 (**2a**) and CCDC 177293 (**8d**). Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].
19. Sheldrick, G. M. *Acta Crystallogr.* **1990**, *A46*, 467–473.
20. Sheldrick, G. M. *SHELX-93: A Computer Program for Determination of Crystal Structure*; University of Göttingen: Germany, 1994.
21. Sheldrick, G. M. *SHELX-97: A Computer Program for Determination of Crystal Structure*; University of Göttingen: Germany, 1999.
22. Ibers, J. A., Hamilton, W. C., eds. *International Tables of X-ray Crystallography*, Kynoch Press: Birmingham, 1974; Vol. IV, pp 99–100 and 149.