Available online at www.sciencedirect.com
ScienceDirect
Tetrahedron
Tetrahedron 62 (2006) 9135–9145

Spontaneous Nef reaction of 3-aryl-2-(diethoxyphosphoryl)-4-nitroalkanoic acids

Henryk Krawczyk,[a,*] Łukasz Albrecht,[a] Jakub Wojciechowski[b] and Wojciech M. Wolf[b]

[a]*Technical University (Politechnika), Institute of Organic Chemistry, Żeromskiego 116, 90-924 Łódź, Poland*
[b]*Technical University (Politechnika), Institute of General and Ecological Chemistry, Żeromskiego 116, 90-924 Łódź, Poland*

Received 28 April 2006; revised 25 June 2006; accepted 13 July 2006
Available online 8 August 2006

Abstract—Spontaneous Nef reaction of primary and secondary 3-aryl-2-(diethoxyphosphoryl)-4-nitroalkanoic acids has been observed for the first time. The reaction provides a general and effective, highly diastereoselective synthesis of 3-(diethoxyphosphoryl)-1-hydroxysuccinimides and 2-(diethoxyphosphoryl)-4-oxoalkanoic acids.

1. Introduction

Acid promoted hydrolysis of primary and secondary nitroalkanes to the corresponding carbonyl compounds, commonly known as the Nef reaction, represents a synthetically important transformation.[1–3] The ability to transform a nitroalkane to an aldehyde or ketone makes the nitro group a masked carbonyl group. Considerable effort has been devoted to optimize conditions of this reaction. Within this area, we have recently demonstrated that the carboxylic acid functionality participates as an intramolecular catalyst in the Nef reaction of primary and secondary 2-(diethoxyphosphoryl)-4-nitroalkanoic acids.[4] We have found that this reaction proceeds in water in the absence of any additives. Under these conditions 2-(diethoxyphosphoryl)-4-nitrobutanoic acid underwent conversion into 3-(diethoxyphosphoryl)-1-hydroxysuccinimide, while 2-(diethoxyphosphoryl)-4-nitropentanoic and hexanoic acids afforded the corresponding 2-(diethoxyphosphoryl)-4-oxoalkanoic acids.

Intramolecular catalysis of the Nef reaction represents a conceptually new approach to the preparation of 1-hydroxysuccinimides,[5] and provides an attractive entry to 2-(diethoxyphosphoryl)-4-oxoalkanoic acids.[6–10] The latter transformation would be very valuable in the synthesis of α-diethoxyphosphoryl-γ-butyrolactones. There has been an intense activity in the application of α-diethoxyphosphoryl-γ-lactones for the preparation of their α-alkylidene derivatives by Horner–Wadsworth–Emmons olefination.[11–15] We have recently discovered that these lactones can also be successfully used as starting materials for the preparation of ethyl cyclopropanecarboxylates.[16]

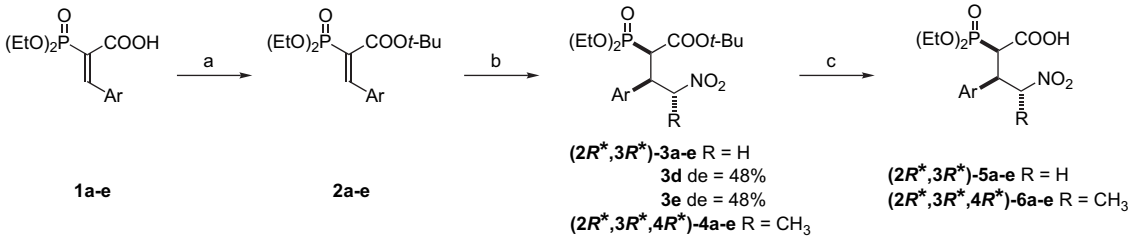
The Nef reaction based on the intramolecular catalysis would significantly benefit from availability of substituted 2-(diethoxyphosphoryl)-4-nitroalkanoic acids. Recently, we have described an efficient route to (*E*)-3-aryl-2-(diethoxyphosphoryl)acrylic acids **1**.[17] In this paper we report that a variety of 3-(diethoxyphosphoryl)-1-hydroxysuccinimides **8a–e** and 2-(diethoxyphosphoryl)-4-oxopentanoic acids **9a–e** can be prepared by addition of nitromethane or nitroethane to the acids **1a–e**, and subsequent spontaneous Nef reaction of the resulting 2-(diethoxyphosphoryl)-4-nitrobutanoic acids **5a–e** and 2-(diethoxyphosphoryl)-4-nitropentanoic acids **6a–e**, respectively.

2. Results and discussion

Our initial attempts to obtain the nitroalkanoic acids **5a–e** and **6a–e** by a self-catalytic Michael addition of nitromethane and nitroethane to the dicyclohexylammonium salts of acids **1a–e** under previously reported conditions were unsuccessful.[4,17] In all cases the unreacted starting materials were recovered. The problem was eventually solved by modifying the Michael acceptor. *tert*-Butyl acrylates **2a–e** were generated by treatment of the acids **1a–e** with *tert*-butyl alcohol in the presence of magnesium sulfate and sulfuric acid (Scheme 1 and Table 1).[18] It was found that the use of the nitroalkane as both the reagent and the solvent with potassium *tert*-butoxide (50 mol %) as a catalyst gave the best results in terms of yield and purity of the products. The addition proceeded effectively at room temperature. The

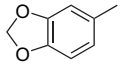
Keywords: Intramolecular catalysis; Nef reaction; Michael reaction; 4-Oxoalkanoic acids; *N*-Hydroxysuccinimides.
* Corresponding author. Fax: +48 42 6365530; e-mail: henkrawc@p.lodz.pl

0040–4020/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2006.07.041



Scheme 1. Reagents and conditions: (a) $MgSO_4$ (5 equiv), H_2SO_4 (1 equiv), *t*-BuOH (4 equiv), CH_2Cl_2, rt; (b) $MeNO_2$ or $EtNO_2$, *t*-BuOK (0.5 equiv), rt; and (c) CF_3COOH–CH_2Cl_2 (1:1), rt, 24 h.

Table 1. *tert*-Butyl acrylates **2**, nitroalkanoates **3** and **4**, and nitroalkanoic acids **5** and **6** prepared

	Ar	**2**		**3** (R=H)		**4** (R=CH_3)		**5**	**6**
		Yield [%]	Reaction time [days]	Yield [%]	Reaction time [days]	Yield [%]	Reaction time [days]	(R=H) Yield [%]	(R=CH_3) Yield [%]
a	4-NO_2–C_6H_4–	82	2	90	1	70	1	90	85
b	4-Br–C_6H_4–	85	2	67	1	66	1	80	89
c	4-CH_3–C_6H_4–	88	4	80	8	49	4	89	84
d	4-CH_3O–C_6H_4–	82	4	56	24	58	5	77	92
e		91	3	73	11	51	5	94	93

yields of the products obtained from nitromethane were similar to those derived from nitroethane. However, the addition of nitromethane to the acrylates **2a–e** was much slower and was highly dependant on the particular electrophile used.

The products **3a–e** and **4a–e** were formed as mixtures of diastereoisomers. Notably, the crystalline nitroalkanoates **3a–c** and **4a–e** were isolated as single diastereoisomers. In each case, the crystalline adduct was the major diastereoisomer present in the reaction mixture. This result indicates that diastereoisomeric products undergo rapid epimerization due to acidic hydrogens at C-2 and C-4 atoms. On the contrary, the crystalline phosphonates **3d** and **3e** were isolated as inseparable mixtures of diastereoisomers, each in a 1:0.35 ratio.

The relative stereochemistry of the stereogenic centers C-2 and C-3 in the phosphonates **3a–c** and **4a–e** was assigned to be (2*R**,3*R**) on the basis of ^1H and ^{13}C NMR data. The values of coupling constants $^3J_{H2–H3}$=10.6–12.2 Hz and $^3J_{P–Cipso}$=14.5–16.4 Hz indicate that the phosphonates exist almost exclusively as a single conformers having antiplanarly oriented phenyl and phosphoryl groups as well as H-2 and H-3 atoms.[19–22]

The relative stereochemistry of the phosphonate **4a** was unequivocally determined to be (2*R**,3*R**,4*R**) by X-ray crystallographic analysis.[23] It is worth noting that the phosphonate **4a** exists in a fully extended zig–zag conformation having the phosphoryl and 4-nitrophenyl groups in antiplanar, and 4-nitrophenyl and methyl groups in gauche positions (Fig. 1). By analogy with the above results the relative configuration of the adducts **4b–e** was assigned to be (2*R**,3*R**,4*R**).

Deprotection of the *tert*-butyl alkanoates **3a–e** and **4a–e** with CF_3COOH afforded crystalline alkanoic acids **5a–e** and **6a–e**, respectively. Notably all the acids were obtained as

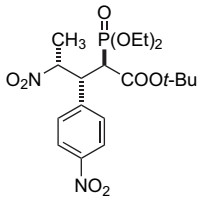
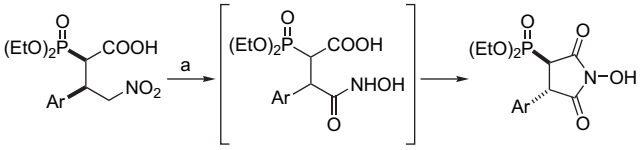


Figure 1. Conformation of the *tert*-butyl (2*R**,3*R**,4*R**)-2-diethoxyphosphoryl-4-nitro-3-(4-nitrophenyl)pentanoate (**4a**).

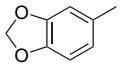
single diastereoisomers. The assignment of the relative configuration of the acids **5a–e** and **6a–e** was based on comparison of their NMR spectral data with those of the respective *tert*-butyl esters **3a–e** and **4a–e**. The acids displayed similar values of the coupling constants $^3J_{H2–H3}$ and $^3J_{P–Cipso}$ to those observed for the esters **3a–e** and **4a–c**. Thus, the relative configuration (2*R**,3*R**) and (2*R**,3*R**,4*R**) could be assigned to the acids **5a–e** and **6a–e**, respectively.

The availability of the requisite nitroalkanoic acids **5a–e** and **6a–e** allowed us to attempt their conversion into 1-hydroxysuccinimides **8a–e** and 4-oxoalkanoic acids **9a–e**, respectively, by the spontaneous Nef reaction. After much experimentation, we found that heating the 4-nitrobutanoic acids **5a–e** in boiling water for 40–70 min was optimal, and provided the desired 1-hydroxysuccinimides **8a–e** in excellent yields (Scheme 2 and Table 2). A noteworthy feature of the Nef reaction is that the formation of the *N*-hydroxysuccinamic acids **7a–e** followed by their ring closure and



Scheme 2. Reagent and condition: (a) H_2O, reflux.

Table 2. 1-Hydroxysuccinimides **8** and 4-oxoalkanoates **10** prepared

	Ar	8		10	
		Yield [%]	Reaction time [min]	Yield [%]	Reaction time [min]
a	4-NO_2–C_6H_4–	60	40	70	120
b	4-Br–C_6H_4–	67	55	56	120
c	4-CH_3–C_6H_4–	68	70	50	120
d	4-CH_3O–C_6H_4–	64	70	62	60
e		79	60	59	90

loss of water occurs with epimerization, giving 1-hydroxysuccinimides **8a–e** as thermodynamically stable trans isomers, exclusively.

Spectroscopic studies were not useful in determining the stereochemistry of imides **8a–e**. X-ray crystallographic analysis conducted on the imide **8b** revealed that the phosphoryl and aryl groups are in trans relationship and allowed us to assign the (3*R**,4*S**) relative stereochemistry to the products **8a–e** (Fig. 2). In this context it is also worth noting that the values of coupling constant $^3J_{P-H4}$=18.0–18.1 Hz observed in ^{1}H NMR spectra of **8a** and **8b** are consistent with the synperiplanar arrangement of the phosphorus and H-4 atoms. The 1-hydroxysuccinimide ring in the crystal structure of **8b** is virtually planar. Deviations from the least-squares mean plane calculated for all endocyclic non-hydrogen atoms are smaller than 0.03 Å. On the contrary to the unsubstituted *N*-hydroxysuccinimide molecule, as reported by Jones,[24] bond lengths of the equivalent endocyclic C–N and C–C bonds are practically equal [N–C3 1.379(5), N–C4 1.372(5), C2–C3 1.524(5), C1–C4 1.517(5) Å]. In the crystal, molecules are linked into centrosymmetric dimers through the hydrogen bonds between the hydroxyl and phosphoryl groups. The respective interatomic O1···O4 [1−*x*, 1−*y*, 1−*z*] distance is 2.599(5) Å. The exocyclic carbonyl bonds are quite short [C3=O2 1.203(4), C4=O3 1.197(4) Å], when compared to the standard values reported for amides and γ-lactams 1.234 and 1.235 Å, respectively[25] and are not involved in the hydrogen bonding.

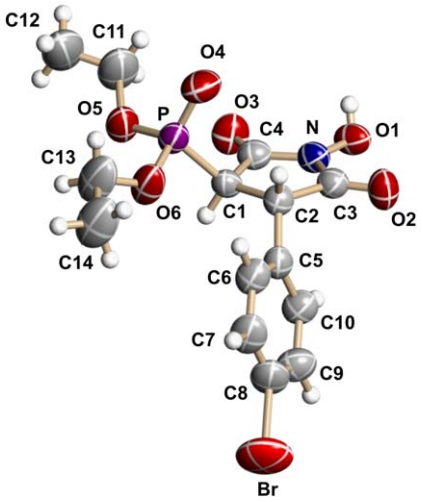
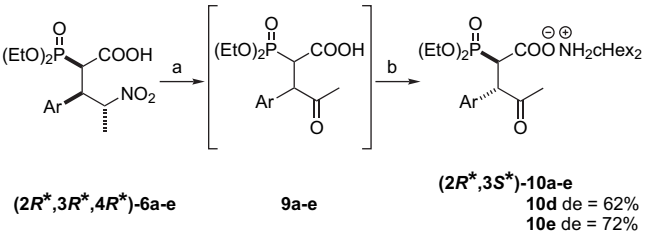


Figure 2. View of **8b** with atom numbering. Displacement ellipsoids were drawn at the 50% probability level.

Next, we focused our attention on converting 4-nitropentanoic acids **6a–e** to the target 4-oxopentanoic acids **9a–e** (Scheme 3). The Nef reaction proceeded effectively in boiling water and it was completed within 1–2 h. The 4-oxoalkanoic acids **9a–e** were then isolated as crystalline dicyclohexylammonium salts **10a–e** in good overall yields (Table 2).



Scheme 3. Reagents and conditions: (a) H_2O, reflux and (b) *c*Hex_2NH (1.1 equiv), CH_2Cl_2, rt.

The stereochemistry of products **10a–e** was similar to that observed for hydroxyimides **8a–e**. The dicyclohexylammonium alkanoates **10a–c** were formed as (2*R**,3*S**) diastereoisomers, exclusively. A notable exception is represented by the products **10d** and **10e** that are formed as mixtures of diastereoisomers of (2*R**,3*S**) and (2*R**,3*R**) in ratios 81:19 and 86:14, respectively. The assignment of the relative configuration was based on ^{1}H and ^{13}C NMR data. It is reasonable to assume that the phosphonates (2*R**,3*S**)-**10a–e** are single conformers with the phosphoryl and acyl groups ($^3J_{P-C=O}$=18.2–19.6 Hz) as well as H-2 and H-3 ($^3J_{H2-H3}$=11.3–11.8 Hz) antiplanar.

3. Conclusions

In conclusion, we have demonstrated that the Nef reaction of primary and secondary 3-aryl-2-(diethoxyphosphoryl)-4-nitroalkanoic acids is assisted by intramolecular catalysis. This reaction provides a general and an efficient methodology for the preparation of the corresponding 3-(diethoxyphosphoryl)-1-hydroxysuccinimides and 2-(diethoxyphosphoryl)-4-oxoalkanoic acids in a highly stereoselective manner.

4. Experimental

4.1. General

NMR spectra were recorded on a Bruker DPX 250 instrument at 250.13 MHz for ^{1}H and 62.9 MHz for ^{13}C and 101.3 MHz for ^{31}P NMR using tetramethylsilane as an internal and 85% H_3PO_4 as an external standard. The multiplicity of carbons was determined by DEPT experiments. IR spectra were measured on a Specord M80 (Zeiss) instrument. Elemental analyses were performed on a Perkin–Elmer PE 2400 analyzer. Melting points were determined in open capillaries and are uncorrected. Acrylic acids **1a–e** were prepared according to the literature procedure.[17]

4.2. General procedure for the preparation of *tert*-butyl (*E*)-3-aryl-2-(diethoxyphosphoryl)acrylates 2a–e

Concentrated sulfuric acid (0.98 g, 10 mmol) was added to a stirred suspension of magnesium sulfate (6.00 g, 50 mmol) in CH_2Cl_2 (40 mL) and the resulting mixture was stirred at

room temperature for 15 min. Acrylic acid **1** (10 mmol) and *tert*-butyl alcohol (2.96 g, 40 mmol) were then added. The mixture was stoppered tightly and was stirred for an appropriate period of time (shown in Table 1) at room temperature. The reaction progress was occasionally monitored with ^{31}P NMR. When the progress of the reaction was no longer observed, saturated $NaHCO_3$ solution was added (50 mL). The organic layer was separated, washed with water (2×20 mL), and dried over $MgSO_4$. Evaporation of the solvent under reduced pressure afforded a crude product, which was purified by column chromatography (eluent: ethyl acetate/hexane 2:1).

4.2.1. *tert*-Butyl (*E*)-2-(diethoxyphosphoryl)-3-(4-nitrophenyl)acrylate (2a). 2.70 g, 82% yield, yellow oil; R_f=0.5 (ethyl acetate/hexane 2:1); IR (film): 1720, 1348, 1256, 1156 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=12.98; ^{1}H NMR ($CDCl_3$): δ=1.39 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.40 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.48 (s, 9H, C(CH_3)$_3$), 4.15–4.28 (m, 4H, 2×CH$_3$CH_2OP), 7.62 (d, 1H, $^3J_{HP}$= 23.8 Hz, ArCH=C), 7.63 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}), 8.24 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}). Anal. calcd for $C_{17}H_{24}NO_7P$: C, 52.99; H, 6.28; N, 3.63. Found: C, 53.11; H, 6.17; N, 3.51.

4.2.2. *tert*-Butyl (*E*)-3-(4-bromophenyl)-2-(diethoxyphosphoryl)acrylate (2b). 3.56 g, 85% yield, pale yellow oil; R_f=0.5 (ethyl acetate/hexane 2:1); IR (film): 1716, 1368, 1252, 1032 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=14.39; ^{1}H NMR ($CDCl_3$): δ=1.37 (t, 6H, $^3J_{HH}$=7.0 Hz, 2×CH_3CH$_2$OP), 1.49 (s, 9H, C(CH_3)$_3$), 4.10–4.25 (m, 4H, 2×CH$_3$CH_2OP), 7.35 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}), 7.49 (d, 1H, $^3J_{HP}$= 24.0 Hz, ArCH=C), 7.51 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}). Anal. calcd for $C_{17}H_{24}BrO_5P$: C, 48.70; H, 5.77. Found: C, 48.79; H, 5.65.

4.2.3. *tert*-Butyl (*E*)-2-(diethoxyphosphoryl)-3-(4-methylphenyl)acrylate (2c). 3.11 g, 88% yield, pale yellow oil; R_f=0.5 (ethyl acetate/hexane 2:1); IR (film): 1716, 1368, 1256, 1024 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=15.37; ^{1}H NMR ($CDCl_3$): δ=1.36 (t, 6H, $^3J_{HH}$=7.1 Hz, 2×CH_3CH$_2$OP), 1.50 (s, 9H, C(CH_3)$_3$), 2.36 (s, 3H, CH_3Ph), 4.13–4.20 (m, 4H, 2×CH$_3$CH_2OP), 7.17 (d, 2H, $^3J_{HH}$=8.0 Hz, 2×CH_{Ar}), 7.39 (d, 2H, $^3J_{HH}$=8.0 Hz, 2×CH_{Ar}), 7.52 (d, 1H, $^3J_{HP}$=24.5 Hz, ArCH=C). Anal. calcd for $C_{18}H_{27}O_5P$: C, 61.01; H, 7.68. Found: C, 61.12; H, 7.79.

4.2.4. *tert*-Butyl (*E*)-2-(diethoxyphosphoryl)-3-(4-methoxyphenyl)acrylate (2d). 3.03g, 82% yield, pale yellow oil; R_f=0.5 (ethyl acetate/hexane 2:1); IR (film): 1716, 1604, 1512, 1368, 1260, 1152, 1028 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=16.30; ^{1}H NMR ($CDCl_3$): δ=1.36 (t, 6H, $^3J_{HH}$=7.0 Hz, 2×CH_3CH$_2$OP), 1.52 (s, 9H, C(CH_3)$_3$), 3.84 (s, 3H, CH_3OPh), 4.08–4.22 (m, 4H, 2×CH$_3$CH_2OP), 6.88 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}), 7.47 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}), 7.49 (d, 1H, $^3J_{HP}$=24.5 Hz, ArCH=C). Anal. calcd for $C_{18}H_{27}O_6P$: C, 58.37; H, 7.35. Found: C, 58.28; H, 7.27.

4.2.5. *tert*-Butyl (*E*)-2-(diethoxyphosphoryl)-3-(3,4-methylenedioxyphenyl)acrylate (2e). 3.49 g, 91% yield, pale yellow oil; R_f=0.5 (ethyl acetate/hexane 2:1); IR (film): 1716, 1368, 1256, 1028 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=15.56; ^{1}H NMR ($CDCl_3$): δ=1.37 (t, 6H, $^3J_{HH}$=7.0 Hz, 2×CH_3CH$_2$OP), 1.53 (s, 9H, C(CH_3)$_3$), 4.09–4.24 (m, 4H, 2×CH$_3$CH_2OP), 6.00 (s, 2H, CH_2O$_2$Ph), 6.80 (d, 1H, $^3J_{HH}$=8.5 Hz, CH_{Ar}), 7.01 (d, 1H, $^3J_{HH}$=8.5 Hz, CH_{Ar}), 7.04 (s, 1H, CH_{Ar}), 7.43 (d, 1H, $^3J_{HP}$=24.5 Hz, ArCH=C). Anal. calcd for $C_{18}H_{25}O_7P$: C, 56.25; H, 6.56. Found: C, 56.34; H, 6.64.

4.3. General procedure for the preparation of *tert*-butyl 3-aryl-2-(diethoxyphosphoryl)-4-nitroalkanoates 3a–e and 4a–e

To a solution of a corresponding *tert*-butyl acrylate **2** (5 mmol) in nitromethane (20 mL) or nitroethane (10 mL) was added potassium *tert*-butoxide (280 mg, 2.5 mmol). The reaction mixture was left at room temperature for an appropriate period of time. The reaction progress was occasionally monitored with ^{31}P NMR. After the acrylate **2** completely reacted the solvent was evaporated and residue was taken up in CH_2Cl_2 (25 mL), washed with H_2O (2×15 mL), and dried over $MgSO_4$. Evaporation of the solvent under reduced pressure afforded a crude product, which was purified by crystallization from diethyl ether to give pure alkanoates **3** and **4**.

4.3.1. *tert*-Butyl 2-(diethoxyphosphoryl)-4-nitro-3-(4-nitrophenyl)butanoate (3a). Crude product: ^{31}P NMR ($CDCl_3$): δ=19.02, 19.32 (0.42:1); (2*R**,3*R**)-**3a**: (2.01 g, 90% yield), white crystals, mp 164–168 °C; IR (CCl_4): 1736, 1552, 1348, 1280, 1160, 1020 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=19.32; ^{1}H NMR ($CDCl_3$): δ=1.17 (s, 9H, C(CH_3)$_3$), 1.36 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.39 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 3.35 (dd, 1H, $^2J_{HP}$= 20.1 Hz, $^3J_{HH}$=11.8 Hz, PCHCOO*t*-Bu), 4.18–4.30 (m, 5H, 2×CH$_3$CH_2OP, CHAr), 4.75 (dd, 1H, $^2J_{HH}$=13.5 Hz, $^3J_{HH}$=10.6 Hz, ArCHCH_AH$_B$NO$_2$), 5.27 (dd, 1H, $^2J_{HH}$=13.5 Hz, $^3J_{HH}$=4.1 Hz, ArCHCH$_A$$H_BNO_2$), 7.44 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}), 8.20 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ=16.11 (d, $^3J_{CP}$=5.4 Hz, *C*H$_3$CH$_2$OP), 16.19 (d, $^3J_{CP}$=5.2 Hz, *C*H$_3$CH$_2$OP), 27.23 (C(*C*H$_3$)$_3$), 42.22 (d, $^2J_{CP}$=3.4 Hz, Ar*C*H), 49.24 (d, $^1J_{CP}$=128.5 Hz, P*C*HCOO*t*-Bu), 63.32 (d, $^2J_{CP}$=3.0 Hz, CH$_3$*C*H$_2$OP), 63.42 (d, $^2J_{CP}$=3.9 Hz, CH$_3$*C*H$_2$OP), 77.89 (*C*H$_2$NO$_2$), 82.77 (*C*(CH$_3$)$_3$), 123.61 (*C*H$_{Ar}$), 129.27 (*C*H$_{Ar}$), 144.55 (d, $^3J_{CP}$=15.7 Hz, *C*$_{Ar}$), 146.91 (*C*$_{Ar}$), 165.07 (d, $^3J_{CP}$=6.0 Hz, PCH*C*OO*t*-Bu). Anal. calcd for $C_{18}H_{27}N_2O_9P$: C, 48.43; H, 6.10; N, 6.28. Found: C, 48.53; H, 6.18; N, 6.20.

4.3.2. *tert*-Butyl 3-(4-bromophenyl)-2-(diethoxyphosphoryl)-4-nitrobutanoate (3b). Crude product: ^{31}P NMR ($CDCl_3$): δ=19.63, 19.99 (0.38:1); (2*R**,3*R**)-**3b**: (1.61 g, 67% yield), white crystals, mp 144–146 °C; IR (CCl_4): 1736, 1552, 1276, 1240, 1224, 1160, 1060, 992, 976 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=19.99; ^{1}H NMR ($CDCl_3$): δ=1.17 (s, 9H, C(CH_3)$_3$), 1.38 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.40 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 3.28 (dd, 1H, $^2J_{HP}$= 19.6 Hz, $^3J_{HH}$=11.9 Hz, PCHCOO*t*-Bu), 4.01–4.15 (m, 1H, CHAr), 4.18–4.29 (m, 4H, 2×CH$_3$CH_2OP), 4.66 (dd, 1H, $^2J_{HH}$=13.2 Hz, $^3J_{HH}$=10.7 Hz, ArCHCH_AH$_B$NO$_2$), 5.20 (dd, 1H, $^2J_{HH}$=13.2 Hz, $^3J_{HH}$=4.1 Hz, ArCHCH$_A$$H_BNO_2$), 7.13 (d, 2H, $^3J_{HH}$=8.5 Hz, 2×CH_{Ar}), 7.44 (d, 2H, $^3J_{HH}$=8.5 Hz, 2×CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ=16.03

(d, $^3J_{CP}$=5.8 Hz, *C*H$_3$CH$_2$OP), 16.15 (d, $^3J_{CP}$=5.6 Hz, *C*H$_3$CH$_2$OP), 27.14 (C(*C*H$_3$)$_3$), 42.03 (d, $^2J_{CP}$=3.7 Hz, Ar*C*H), 49.49 (d, $^1J_{CP}$=128.1 Hz, P*C*HCOO*t*-Bu), 63.07 (d, $^2J_{CP}$=3.2 Hz, CH$_3$*C*H$_2$OP), 63.18 (d, $^2J_{CP}$=2.4 Hz, CH$_3$*C*H$_2$OP), 78.26 (*C*H$_2$NO$_2$), 82.30 (*C*(CH$_3$)$_3$), 121.91 (*C*$_{Ar}$), 129.76 (*C*H$_{Ar}$), 131.55 (*C*H$_{Ar}$), 135.95 (d, $^3J_{CP}$=15.9 Hz, *C*$_{Ar}$), 165.18 (d, $^3J_{CP}$=7.0 Hz, PCH*C*OO*t*-Bu). Anal. calcd for $C_{18}H_{27}BrNO_7P$: C, 45.01; H, 5.67; N, 2.92. Found: C, 45.11; H, 5.71; N, 2.80.

4.3.3. *tert*-Butyl 2-(diethoxyphosphoryl)-3-(4-methylphenyl)-4-nitrobutanoate (3c). Crude product: ^{31}P NMR (CDCl$_3$): δ=20.13, 20.61 (0.39:1); (2*R**,3*R**)-**3c**: (1.66 g, 80% yield), white crystals, mp 79–81 °C; IR (CCl$_4$): 1728, 1556, 1248, 1156, 1024 cm^{-1}; ^{31}P NMR (CDCl$_3$): δ=20.61; ^{1}H NMR (CDCl$_3$): δ=1.14 (s, 9H, C(C*H*$_3$)$_3$), 1.37 (t, 3H, $^3J_{HH}$=7.0 Hz, C*H*$_3$CH$_2$OP), 1.41 (t, 3H, $^3J_{HH}$=7.0 Hz, C*H*$_3$CH$_2$OP), 2.29 (s, 3H, C*H*$_3$Ph), 3.30 (dd, 1H, $^2J_{HP}$=19.3 Hz, $^3J_{HH}$=12.0 Hz, PC*H*COO*t*-Bu), 3.98–4.09 (m, 1H, C*H*Ar), 4.17–4.31 (m, 4H, 2×CH$_3$C*H*$_2$OP), 4.66 (dd, 1H, $^2J_{HH}$=12.8 Hz, $^3J_{HH}$=10.8 Hz, ArCHC*H*$_A$H$_B$NO$_2$), 5.18 (dd, 1H, $^2J_{HH}$=12.8 Hz, $^3J_{HH}$=4.0 Hz, ArCHCH$_A$*H*$_B$NO$_2$), 7.10 (s, 4H, 4×C*H*$_{Ar}$); ^{13}C NMR (CDCl$_3$): δ=15.98 (d, $^3J_{CP}$=6.0 Hz, *C*H$_3$CH$_2$OP), 16.08 (d, $^3J_{CP}$=5.9 Hz, *C*H$_3$CH$_2$OP), 20.67 (*C*H$_3$Ph), 27.02 (C(*C*H$_3$)$_3$), 42.20 (d, $^2J_{CP}$=3.8 Hz, Ar*C*H), 49.74 (d, $^1J_{CP}$=127.6 Hz, P*C*HCOO*t*-Bu), 62.88 (d, $^2J_{CP}$=3.4 Hz, CH$_3$*C*H$_2$OP), 62.93 (d, $^2J_{CP}$=3.7 Hz, CH$_3$*C*H$_2$OP), 78.70 (*C*H$_2$NO$_2$), 81.86 (*C*(CH$_3$)$_3$), 127.76 (*C*H$_{Ar}$), 128.96 (*C*H$_{Ar}$), 133.58 (d, $^3J_{CP}$=15.8 Hz, *C*$_{Ar}$), 137.51 (*C*$_{Ar}$), 165.28 (d, $^3J_{CP}$=5.4 Hz, PCH*C*OO*t*-Bu). Anal. calcd for $C_{19}H_{30}NO_7P$: C, 54.93; H, 7.28; N, 3.37. Found: C, 54.77; H, 7.37; N, 3.26.

4.3.4. *tert*-Butyl 2-(diethoxyphosphoryl)-3-(4-methoxyphenyl)-4-nitrobutanoate (3d). 1.21 g, 56% yield, white crystals, mp 93–95 °C; IR (CCl$_4$): 1728, 1556, 1252, 1148, 1024 cm^{-1}; ^{31}P NMR (CDCl$_3$): δ=20.13, 20.55 (0.35:1); ^{1}H NMR (CDCl$_3$): δ=1.16 (s, 9H, C(C*H*$_3$)$_3$, major), 1.28 (t, 3H, $^3J_{HH}$=7.0 Hz, C*H*$_3$CH$_2$OP, minor), 1.30 (t, 3H, $^3J_{HH}$=7.0 Hz, C*H*$_3$CH$_2$OP, minor), 1.38 (t, 3H, $^3J_{HH}$=7.2 Hz, C*H*$_3$CH$_2$OP, major), 1.41 (t, 3H, $^3J_{HH}$=7.2 Hz, C*H*$_3$CH$_2$OP, major), 1.46 (s, 9H, C(C*H*$_3$)$_3$, minor), 3.23 (dd, 1H, $^2J_{HP}$=23.2 Hz, $^3J_{HH}$=6.2 Hz, PC*H*COO*t*-Bu, minor), 3.28 (dd, 1H, $^2J_{HP}$=19.2 Hz, $^3J_{HH}$=12.0 Hz, PC*H*COO*t*-Bu, major), 3.76 (s, 3H, C*H*$_3$OPh, major), 3.78 (s, 3H, C*H*$_3$OPh, minor), 3.98–4.29 (m, 5H, 2×CH$_3$C*H*$_2$OP, C*H*Ar), 4.64 (dd, 1H, $^2J_{HH}$=13.0 Hz, $^3J_{HH}$=11.0 Hz, ArCHC*H*$_A$H$_B$NO$_2$, major), 5.07 (d, 2H, $^3J_{HH}$=7.5 Hz, ArCHC*H*$_2$NO$_2$, minor), 5.18 (dd, 1H, $^2J_{HH}$=13.0 Hz, $^3J_{HH}$=4.0 Hz, ArCHCH$_A$*H*$_B$NO$_2$, major), 6.79–6.86 (m, 2H, 2×C*H*$_{Ar}$), 7.12–7.20 (m, 2H, 2×C*H*$_{Ar}$); ^{13}C NMR (CDCl$_3$): δ=15.98 (d, $^3J_{CP}$=5.4 Hz, *C*H$_3$CH$_2$OP), 16.06 (d, $^3J_{CP}$=5.6 Hz, *C*H$_3$CH$_2$OP), 27.06 (C(*C*H$_3$)$_3$, major), 27.46 (C(*C*H$_3$)$_3$, minor), 41.11 (d, $^2J_{CP}$=2.6 Hz, Ar*C*H, minor), 41.89 (d, $^2J_{CP}$=3.5 Hz, Ar*C*H, major), 49.84 (d, $^1J_{CP}$=127.4 Hz, P*C*HCOO*t*-Bu, major), 50.58 (d, $^1J_{CP}$=129.4 Hz, P*C*HCOO*t*-Bu, minor), 54.85 (*C*H$_3$OPh), 62.44 (d, $^2J_{CP}$=7.3 Hz, CH$_3$*C*H$_2$OP, minor), 62.69 (d, $^2J_{CP}$=6.9 Hz, CH$_3$*C*H$_2$OP, minor), 62.91 (d, $^2J_{CP}$=6.0 Hz, CH$_3$*C*H$_2$OP, major), 77.27 (d, $^3J_{CP}$=8.4 Hz, *C*H$_2$NO$_2$, minor), 78.75 (*C*H$_2$NO$_2$, major), 81.84 (*C*(CH$_3$)$_3$, major), 82.61 (*C*(CH$_3$)$_3$, minor), 113.69 (*C*H$_{Ar}$, major), 113.84 (*C*H$_{Ar}$, minor), 128.64 (d, $^3J_{CP}$=16.0 Hz, *C*$_{Ar}$, major), 128.68 (*C*H$_{Ar}$, minor), 129.02 (*C*H$_{Ar}$, major), 129.11 (d, $^3J_{CP}$=11.8 Hz, *C*$_{Ar}$, minor), 159.07 (*C*$_{Ar}$), 165.30 (d, $^3J_{CP}$=5.2 Hz, PCH*C*OO*t*-Bu, major), 166.33 (d, $^3J_{CP}$=4.1 Hz, PCH*C*OO*t*-Bu, minor). Anal. calcd for $C_{19}H_{30}NO_8P$: C, 52.90; H, 7.01; N, 3.25. Found: C, 52.99; H, 7.12; N, 3.36.

4.3.5. *tert*-Butyl 2-(diethoxyphosphoryl)-3-(3,4-methylenedioxyphenyl)-4-nitrobutanoate (3e). 1.62 g, 73% yield, white crystals, mp 83–86 °C; IR (CCl$_4$): 1732, 1556, 1248, 1148, 1044 cm^{-1}; ^{31}P NMR (CDCl$_3$): δ=19.97, 20.35 (0.35:1); ^{1}H NMR (CDCl$_3$): δ=1.21 (s, 9H, C(C*H*$_3$)$_3$, major), 1.30 (t, 3H, $^3J_{HH}$=7.0 Hz, C*H*$_3$CH$_2$OP, minor), 1.32 (t, 3H, $^3J_{HH}$=7.0 Hz, C*H*$_3$CH$_2$OP, minor), 1.38 (t, 3H, $^3J_{HH}$=7.2 Hz, C*H*$_3$CH$_2$OP, major), 1.41 (t, 3H, $^3J_{HH}$=7.2 Hz, C*H*$_3$CH$_2$OP, major), 1.46 (s, 9H, C(C*H*$_3$)$_3$, minor), 3.20 (dd, 1H, $^2J_{HP}$=23.2 Hz, $^3J_{HH}$=6.0 Hz, PC*H*COO*t*-Bu, minor), 3.24 (dd, 1H, $^2J_{HP}$=19.5 Hz, $^3J_{HH}$=12.0 Hz, PC*H*COO*t*-Bu, major), 3.95–4.30 (m, 5H, 2×CH$_3$C*H*$_2$OP, C*H*Ar), 4.63 (dd, 1H, $^2J_{HH}$=13.0 Hz, $^3J_{HH}$=10.8 Hz, ArCHC*H*$_A$H$_B$NO$_2$, major), 5.06 (d, 1H, $^3J_{HH}$=4.2 Hz, ArCHC*H*$_2$NO$_2$, minor), 5.09 (s, 1H, ArCHC*H*$_2$NO$_2$, minor), 5.17 (dd, 1H, $^2J_{HH}$=13.0 Hz, $^3J_{HH}$=4.0 Hz, ArCHCH$_A$*H*$_B$NO$_2$, major), 5.93 (s, 2H, C*H*$_2$O$_2$Ph, major), 5.94 (s, 2H, C*H*$_2$O$_2$Ph, minor), 6.70–6.74 (m, 3H, 3×C*H*$_{Ar}$); ^{13}C NMR (CDCl$_3$): δ=16.00 (d, $^3J_{CP}$=5.6 Hz, *C*H$_3$CH$_2$OP), 16.08 (d, $^3J_{CP}$=5.7 Hz, *C*H$_3$CH$_2$OP), 27.15 (C(*C*H$_3$)$_3$, major), 27.49 (C(*C*H$_3$)$_3$, minor), 41.55 (d, $^2J_{CP}$=3.5 Hz, Ar*C*H, minor), 42.36 (d, $^2J_{CP}$=3.3 Hz, Ar*C*H, major), 49.87 (d, $^1J_{CP}$=127.4 Hz, P*C*HCOO*t*-Bu, major), 50.58 (d, $^1J_{CP}$=129.1 Hz, P*C*HCOO*t*-Bu, minor), 62.53 (d, $^2J_{CP}$=7.0 Hz, CH$_3$*C*H$_2$OP, minor), 62.79 (d, $^2J_{CP}$=5.4 Hz, CH$_3$*C*H$_2$OP, minor), 62.92 (d, $^2J_{CP}$=3.6 Hz, CH$_3$*C*H$_2$OP, major), 63.02 (d, $^2J_{CP}$=2.3 Hz, CH$_3$*C*H$_2$OP, major), 77.16 (d, $^3J_{CP}$=8.1 Hz, *C*H$_2$NO$_2$, minor), 78.67 (*C*H$_2$NO$_2$, major), 81.97 (*C*(CH$_3$)$_3$, major), 82.76 (*C*(CH$_3$)$_3$, minor), 100.91 (CH$_2$O$_2$Ph), 107.78 (*C*H$_{Ar}$, minor), 107.99 (*C*H$_{Ar}$, major), 108.09 (*C*H$_{Ar}$), 121.05 (*C*H$_{Ar}$, minor), 121.57 (*C*H$_{Ar}$, major), 130.27 (d, $^3J_{CP}$=16.1 Hz, *C*$_{Ar}$, major), 130.98 (d, $^3J_{CP}$=11.8 Hz, *C*$_{Ar}$, minor), 147.09 (*C*$_{Ar}$), 147.51 (*C*$_{Ar}$, major), 147.68 (*C*$_{Ar}$, minor), 165.22 (d, $^2J_{CP}$=5.6 Hz, PCH*C*OO*t*-Bu, major), 166.28 (d, $^2J_{CP}$=3.8 Hz, PCH*C*OO*t*-Bu, minor). Anal. calcd for $C_{19}H_{28}NO_9P$: C, 51.24; H, 6.34; N, 3.14. Found: C, 51.33; H, 6.22; N, 3.21.

4.3.6. *tert*-Butyl 2-(diethoxyphosphoryl)-4-nitro-3-(4-nitrophenyl)pentanoate (4a). Crude product: ^{31}P NMR (CDCl$_3$): δ=19.30, 19.34, 19.96, 20.43 (1:0.31:0.28:0.62); (2*R**,3*R**,4*R**)-**4a**: (1.61 g, 70% yield), white crystals, mp 216–218 °C; IR (CCl$_4$): 1724, 1544, 1348, 1248, 1156, 1020 cm^{-1}; ^{31}P NMR (CDCl$_3$): δ=19.30; ^{1}H NMR (CDCl$_3$): δ=1.17 (s, 9H, C(C*H*$_3$)$_3$), 1.38–1.44 (m, 6H, 2×C*H*$_3$CH$_2$OP), 1.42 (d, 3H, $^3J_{HH}$=6.8 Hz, C*H*$_3$CHNO$_2$), 3.37 (dd, 1H, $^2J_{HP}$=21.0 Hz, $^3J_{HH}$=11.8 Hz, PC*H*COO*t*-Bu), 4.17–4.30 (m, 4H, 2×CH$_3$C*H*$_2$OP), 4.41 (ddd, 1H, $^3J_{HH}$=11.8, $^3J_{HP}$=8.6 Hz, $^3J_{HH}$=4.7 Hz, Ar–C*H*), 5.42 (dq, 1H, $^3J_{HH}$=6.8 Hz, $^3J_{HH}$=4.7 Hz, CH$_3$C*H*NO$_2$), 7.36 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×C*H*$_{Ar}$), 8.18 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×C*H*$_{Ar}$); ^{13}C NMR (CDCl$_3$): δ=12.60 (*C*H$_3$CHNO$_2$), 16.19 (2×*C*H$_3$CH$_2$OP), 27.22 (C(*C*H$_3$)$_3$), 47.06 (Ar*C*H), 48.34 (d, $^1J_{CP}$=129.5 Hz, P*C*HCOO*t*-Bu), 63.32 (d, $^2J_{CP}$=5.7 Hz, CH$_3$*C*H$_2$OP), 63.40 (d, $^2J_{CP}$=5.0 Hz, CH$_3$*C*H$_2$OP), 82.82 (d, $^3J_{CP}$=7.0 Hz, CH$_3$*C*HNO$_2$), 83.01

($C(CH_3)_3$), 123.21 (CH_{Ar}), 130.26 (CH_{Ar}), 141.98 (d, $^3J_{CP}$=14.5 Hz, C_{Ar}), 147.58 (C_{Ar}), 165.21 (PCH*C*OO*t*-Bu). Anal. calcd for $C_{19}H_{29}N_2O_9P$: C, 49.56; H, 6.35; N, 6.08. Found: C, 49.67; H, 6.47; N, 6.00.

4.3.7. *tert*-Butyl 3-(4-bromophenyl)-2-(diethoxyphosphoryl)-4-nitropentanoate (4b). Crude product: ^{31}P NMR ($CDCl_3$): δ=19.97, 20.77, 21.23 (1:0.15:0.39); (2*R**,3*R**,4*R**)-**4b**: (1.63 g, 66% yield), white crystals, mp 172–174 °C; IR (CCl_4): 1724, 1548, 1392, 1288, 1248, 1156, 1024 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=19.97; ^{1}H NMR ($CDCl_3$): δ=1.16 (s, 9H, C(CH_3)$_3$), 1.34–1.44 (m, 6H, 2×CH_3CH$_2$OP), 1.40 (d, 3H, $^3J_{HH}$=6.5 Hz, CH_3CHNO$_2$), 3.33 (dd, 1H, $^2J_{HP}$=20.5 Hz, $^3J_{HH}$=12.0 Hz, PC*H*COO*t*-Bu), 4.17–4.32 (m, 5H, 2×CH$_3$CH_2OP, Ar–C*H*), 5.34 (dq, 1H, $^3J_{HH}$=6.5 Hz, $^3J_{HH}$=4.5 Hz, CH$_3$C*H*NO$_2$), 7.02 (d, 2H, $^3J_{HH}$=8.5 Hz, 2×CH_{Ar}), 7.43 (d, 2H, $^3J_{HH}$=8.5 Hz, 2×CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ=12.29 (*C*H$_3$CHNO$_2$), 16.09 (d, $^3J_{CP}$=3.4 Hz, *C*H$_3$CH$_2$OP), 16.19 (d, $^3J_{CP}$=3.3 Hz, *C*H$_3$CH$_2$OP), 27.14 (C(*C*H$_3$)$_3$), 46.79 (d, $^2J_{CP}$=3.0 Hz, Ar*C*H), 48.52 (d, $^1J_{CP}$=129.1 Hz, P*C*HCOO*t*-Bu), 63.04 (d, $^2J_{CP}$=7.3 Hz, CH$_3$*C*H$_2$OP), 63.20 (d, $^2J_{CP}$=6.4 Hz, CH$_3$*C*H$_2$OP), 82.36 (*C*(CH$_3$)$_3$), 83.10 (CH$_3$*C*HNO$_2$), 122.18 (C_{Ar}), 130.77 (CH_{Ar}), 131.25 (CH_{Ar}), 133.31 (d, $^3J_{CP}$=16.0 Hz, C_{Ar}), 165.32 (d, $^2J_{CP}$=6.3 Hz, PCH*C*OO*t*-Bu). Anal. calcd for $C_{19}H_{29}BrNO_7P$: C, 46.17; H, 5.19; N, 2.83. Found: C, 46.28; H, 5.27; N, 2.95.

4.3.8. *tert*-Butyl 2-(diethoxyphosphoryl)-3-(4-methylphenyl)-4-nitropentanoate (4c). Crude product: ^{31}P NMR ($CDCl_3$): δ=20.45, 20.63, 21.27, 21.91, (0.19:1:0.16:0.45); (2*R**,3*R**,4*R**)-**4c**: (1.05 g, 49% yield), white crystals, mp 133–135 °C; IR (CCl_4): 1732, 1552, 1392, 1368, 1252, 1160, 1028 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=20.63; ^{1}H NMR ($CDCl_3$): δ=1.12 (s, 9H, C(CH_3)$_3$), 1.35–1.44 (m, 6H, 2×CH_3CH$_2$OP), 1.41 (d, 3H, $^3J_{HH}$=6.5 Hz, CH_3CHNO$_2$), 2.29 (s, 3H, CH_3Ph), 3.36 (dd, 1H, $^2J_{HP}$=19.9 Hz, $^3J_{HH}$= 12.2 Hz, PC*H*COO*t*-Bu), 4.19–4.30 (m, 5H, 2×CH$_3$CH_2OP, Ar–C*H*), 5.32 (dq, 1H, $^3J_{HH}$=6.5 Hz, $^3J_{HH}$=4.4 Hz, CH$_3$C*H*NO$_2$), 6.98 (d, 2H, $^3J_{HH}$=8.0 Hz, 2×CH_{Ar}), 7.08 (d, 2H, $^3J_{HH}$=8.0 Hz, 2×CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ= 12.11 (*C*H$_3$CHNO$_2$), 16.09 (d, $^3J_{CP}$=5.5 Hz, *C*H$_3$CH$_2$OP), 16.18 (d, $^3J_{CP}$=5.2 Hz, *C*H$_3$CH$_2$OP), 20.80 (*C*H$_3$Ph), 27.06 (C(*C*H$_3$)$_3$), 47.00 (d, $^2J_{CP}$=3.2 Hz, Ar*C*H), 48.80 (d, $^1J_{CP}$=128.7 Hz, P*C*HCOO*t*-Bu), 62.94 (d, $^2J_{CP}$=7.6 Hz, CH$_3$*C*H$_2$OP), 63.06 (d, $^2J_{CP}$=7.6 Hz, CH$_3$*C*H$_2$OP), 81.96 (*C*(CH$_3$)$_3$), 83.41 (CH$_3$*C*HNO$_2$), 128.73 (CH_{Ar}), 128.90 (CH_{Ar}), 130.95 (d, $^3J_{CP}$=15.7 Hz, C_{Ar}), 137.70 (C_{Ar}), 165.51 (d, $^2J_{CP}$=6.2 Hz, PCH*C*OO*t*-Bu). Anal. calcd for $C_{20}H_{32}NO_7P$: C, 55.94; H, 7.51; N, 3.26. Found: C, 55.77; H, 7.64; N, 3.11.

4.3.9. *tert*-Butyl 2-(diethoxyphosphoryl)-3-(4-methoxyphenyl)-4-nitropentanoate (4d). Crude product: ^{31}P NMR ($CDCl_3$): δ=20.58, 21.00, 21.54 (1:0.14:0.41); (2*R**,3*R**,4*R**)-**4d**: (1.29 g, 58% yield), white crystals, mp 138–140 °C; IR (CCl_4): 1728, 1512, 1392, 1368, 1252, 1160, 1024 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=20.58; ^{1}H NMR ($CDCl_3$): δ=1.14 (s, 9H, C(CH_3)$_3$), 1.33–1.44 (m, 9H, 2×CH_3CH$_2$OP, CH_3CHNO$_2$), 3.34 (dd, 1H, $^2J_{HP}$=20.0 Hz, $^3J_{HH}$=12.2 Hz, PC*H*COO*t*-Bu), 3.77 (s, 3H, CH_3OPh), 4.18–4.31 (m, 5H, 2×CH$_3$CH_2OP, Ar–C*H*), 5.30 (dq, 1H, $^3J_{HH}$=6.5 Hz, $^3J_{HH}$=4.2 Hz, CH$_3$C*H*NO$_2$), 6.81 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}), 7.03 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ=12.11 (*C*H$_3$CHNO$_2$), 16.09 (d, $^3J_{CP}$=4.8 Hz, *C*H$_3$CH$_2$OP), 16.17 (d, $^3J_{CP}$= 5.7 Hz, *C*H$_3$CH$_2$OP), 27.13 (C(*C*H$_3$)$_3$), 46.68 (d, $^2J_{CP}$= 3.3 Hz, Ar*C*H), 48.89 (d, $^1J_{CP}$=128.7 Hz, P*C*HCOO*t*-Bu), 54.98 (*C*H$_3$OPh), 62.94 (d, $^2J_{CP}$=7.8 Hz, CH$_3$*C*H$_2$OP), 63.06 (d, $^2J_{CP}$=7.4 Hz, CH$_3$*C*H$_2$OP), 82.00 (*C*(CH$_3$)$_3$), 83.48 (CH$_3$*C*HNO$_2$), 113.45 (CH_{Ar}), 125.95 (d, $^3J_{CP}$= 16.4 Hz, C_{Ar}), 130.14 (CH_{Ar}), 159.26 (C_{Ar}), 165.54 (d, $^2J_{CP}$=6.0 Hz, PCH*C*OO*t*-Bu). Anal. calcd for $C_{20}H_{32}NO_8P$: C, 53.93; H, 7.24; N, 3.14. Found: C, 53.77; H, 7.35; N, 3.01.

4.3.10. *tert*-Butyl 2-(diethoxyphosphoryl)-3-(3,4-methylenedioxyphenyl)-4-nitropentanoate (4e). Crude product: ^{31}P NMR ($CDCl_3$): δ=20.34, 21.04, 21.53 (1:0.14:0.39); (2*R**,3*R**,4*R**)-**4e**: (1.17 g, 51% yield), white crystals, mp 101–107 °C; IR (CCl_4): 1728, 1552, 1488, 1444, 1392, 1368, 1256, 1160, 1032 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=20.34; ^{1}H NMR ($CDCl_3$): δ=1.19 (s, 9H, C(CH_3)$_3$), 1.35–1.46 (m, 9H, 2×CH_3CH$_2$OP, CH_3CHNO$_2$), 3.29 (dd, 1H, $^2J_{HP}$=20.0 Hz, $^3J_{HH}$=12.2 Hz, PC*H*COO*t*-Bu), 4.18–4.31 (m, 5H, 2×CH$_3$CH_2OP, Ar–C*H*), 5.29 (dq, 1H, $^3J_{HH}$=6.5 Hz, $^3J_{HH}$=4.5 Hz, CH$_3$C*H*NO$_2$), 5.92–5.94 (m, 2H, CH_2O$_2$Ph), 6.57 (dd, 1H, $^3J_{HH}$=8.0 Hz, $^4J_{HH}$=1.8 Hz, CH_{Ar}), 6.62 (d, 1H, $^4J_{HH}$=1.8 Hz, CH_{Ar}), 6.72 (d, 1H, $^3J_{HH}$=8.0 Hz, CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ=12.19 (*C*H$_3$CHNO$_2$), 16.11 (d, $^3J_{CP}$=5.9 Hz, *C*H$_3$CH$_2$OP), 16.19 (d, $^3J_{CP}$=4.2 Hz, *C*H$_3$CH$_2$OP), 27.21 (C(*C*H$_3$)$_3$), 47.09 (Ar*C*H), 48.89 (d, $^1J_{CP}$=128.7 Hz, P*C*HCOO*t*-Bu), 62.99 (d, $^2J_{CP}$=7.9 Hz, CH$_3$*C*H$_2$OP), 63.12 (d, $^2J_{CP}$=7.0 Hz, CH$_3$*C*H$_2$OP), 82.09 (*C*(CH$_3$)$_3$), 83.43 (CH$_3$*C*HNO$_2$), 100.98 (*C*H$_2$O$_2$Ph), 107.84 (CH_{Ar}), 109.29 (CH_{Ar}), 122.68 (CH_{Ar}), 127.63 (d, $^3J_{CP}$=16.4 Hz, C_{Ar}), 147.27 (C_{Ar}), 147.39 (C_{Ar}), 165.45 (d, $^2J_{CP}$=6.3 Hz, PCH*C*OO*t*-Bu). Anal. calcd for $C_{20}H_{30}NO_9P$: C, 52.29; H, 6.58; N, 3.05. Found: C, 52.20; H, 6.69; N, 3.17.

4.4. General procedure for the preparation of 3-aryl-2-(diethoxyphosphoryl)-4-nitroalkanoic acids 5a–e and 6a–e

To a solution of a corresponding *tert*-butyl alkanoate **3** or **4** (2.5 mmol) in CH_2Cl_2 (5 mL) was added trifluoroacetic acid (5 mL). The reaction mixture was left at room temperature for 24 h. The solvent was evaporated and residue was taken up in Et_2O (15 mL) and left to crystallize. Filtration of the crystals afforded pure alkanoic acids **5** and **6**.

4.4.1. (2*R,3*R**)-2-(Diethoxyphosphoryl)-4-nitro-3-(4-nitrophenyl)butanoic acid (5a).** 878 mg, 90% yield, white crystals, mp 149–151 °C; IR (CCl_4): 1728, 1552, 1352, 1224, 1152, 1020 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=19.35; ^{1}H NMR (acetone-*d*): δ=1.21 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.22 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 3.64 (dd, 1H, $^2J_{HP}$=20.8 Hz, $^3J_{HH}$=11.5 Hz, PC*H*COOH), 4.04–4.25 (m, 5H, 2×CH$_3$CH_2OP, C*H*Ar), 4.93 (dd, 1H, $^2J_{HH}$=13.5 Hz, $^3J_{HH}$=11.0 Hz, ArCHCH_AH$_B$NO$_2$), 5.30 (dd, 1H, $^2J_{HH}$=13.5 Hz, $^3J_{HH}$=4.1 Hz, ArCHCH$_A$$H_BNO_2$), 7.63 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}), 8.07 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=16.50 (d, $^3J_{CP}$=5.7 Hz, *C*H$_3$CH$_2$OP), 16.57 (d, $^3J_{CP}$=3.5 Hz, *C*H$_3$CH$_2$OP), 43.50 (d, $^2J_{CP}$=3.6 Hz, Ar*C*H), 49.03 (d,

$^{1}J_{CP}$=126.8 Hz, P*C*HCOOH), 64.07 (d, $^{2}J_{CP}$=6.4 Hz, CH_3CH_2OP), 64.17 (d, $^{2}J_{CP}$=6.8 Hz, CH_3CH_2OP), 78.87 (CH_2NO_2), 124.28 (CH_{Ar}), 130.80 (CH_{Ar}), 146.57 (d, $^{3}J_{CP}$=15.5 Hz, C_{Ar}), 148.52 (C_{Ar}), 168.21 (d, $^{2}J_{CP}$=5.7 Hz, PCH*C*OOH). Anal. calcd for $C_{14}H_{19}N_2O_9P$: C, 43.08; H, 4.91; N, 7.18. Found: C, 43.20; H, 4.79; N, 7.11.

4.4.2. (2*R,3*R**)-3-(4-Bromophenyl)-2-(diethoxyphosphoryl)-4-nitrobutanoic acid (5b).** 848 mg, 80% yield, white crystals, mp 128–130 °C; IR (CCl_4): 1732, 1556, 1220, 1172, 1012, 984 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=19.80; ^{1}H NMR (acetone-*d*): δ=1.34 (dt, 3H, $^{3}J_{HH}$=7.1 Hz, $^{4}J_{HP}$=0.5 Hz, CH_3CH$_2$OP), 1.35 (dt, 3H, $^{3}J_{HH}$=7.1 Hz, $^{4}J_{HP}$=0.5 Hz, CH_3CH$_2$OP), 3.66 (dd, 1H, $^{2}J_{HP}$=20.2 Hz, $^{3}J_{HH}$=11.7 Hz, PC*H*COOH), 4.04–4.28 (m, 5H, 2×CH$_3$CH_2OP, C*H*Ar), 4.94 (dd, 1H, $^{2}J_{HH}$=13.2 Hz, $^{3}J_{HH}$=11.1 Hz, ArCHCH_AH$_B$NO$_2$), 5.35 (dd, 1H, $^{2}J_{HH}$=13.2 Hz, $^{3}J_{HH}$=4.2 Hz, ArCHCH$_A$$H_BNO_2$), 7.39 (d, 2H, $^{3}J_{HH}$=8.5 Hz, 2×CH_{Ar}), 7.50 (d, 2H, $^{3}J_{HH}$=8.5 Hz, 2×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=16.55 (d, $^{3}J_{CP}$=3.5 Hz, *C*H$_3$CH$_2$OP), 16.64 (d, $^{3}J_{CP}$=3.3 Hz, *C*H$_3$CH$_2$OP), 43.43 (d, $^{2}J_{CP}$=3.9 Hz, Ar*C*H), 49.32 (d, $^{1}J_{CP}$=126.3 Hz, P*C*HCOOH), 63.94 (d, $^{2}J_{CP}$=6.0 Hz, CH$_3$*C*H$_2$OP), 64.04 (d, $^{2}J_{CP}$=6.5 Hz, CH$_3$*C*H$_2$OP), 79.31 (*C*H$_2$NO$_2$), 121.30 (C_{Ar}), 131.51 (*C*H$_{Ar}$), 132.39 (*C*H$_{Ar}$), 138.34 (d, $^{3}J_{CP}$=15.7 Hz, C_{Ar}), 168.32 (d, $^{2}J_{CP}$=5.6 Hz, PCH*C*OOH). Anal. calcd for $C_{14}H_{19}BrNO_7P$: C, 39.64; H, 4.51; N, 3.30. Found: C, 39.51; H, 4.39; N, 3.40.

4.4.3. (2*R,3*R**)-2-(Diethoxyphosphoryl)-3-(4-methylphenyl)-4-nitrobutanoic acid (5c).** 799 mg, 89% yield, white crystals, mp 112–115 °C; IR (CCl_4): 1736, 1552, 1220, 1040, 1016 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=20.16; ^{1}H NMR (acetone-*d*): δ=1.34 (t, 3H, $^{3}J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 1.35 (t, 3H, $^{3}J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 2.26 (s, 3H, CH_3Ph), 3.60 (dd, 1H, $^{2}J_{HP}$=19.8 Hz, $^{3}J_{HH}$=11.8 Hz, PC*H*COOH), 4.03–4.26 (m, 5H, 2×CH$_3$CH_2OP, C*H*Ar), 4.89 (dd, 1H, $^{2}J_{HH}$=13.0 Hz, $^{3}J_{HH}$=11.2 Hz, ArCHCH_AH$_B$NO$_2$), 5.32 (dd, 1H, $^{2}J_{HH}$=13.0 Hz, $^{3}J_{HH}$=4.2 Hz, ArCHCH$_A$$H_BNO_2$), 7.10 (d, 2H, $^{3}J_{HH}$=7.5 Hz, 2×CH_{Ar}), 7.28 (d, 2H, $^{3}J_{HH}$=7.5 Hz, 2×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=16.41 (d, $^{3}J_{CP}$=4.1 Hz, *C*H$_3$CH$_2$OP), 16.50 (d, $^{3}J_{CP}$=4.1 Hz, *C*H$_3$CH$_2$OP), 20.96 (CH_3Ph), 43.34 (d, $^{2}J_{CP}$=4.2 Hz, Ar*C*H), 49.45 (d, $^{1}J_{CP}$=126.9 Hz, P*C*HCOOH), 64.09 (CH$_3$*C*H$_2$OP), 64.19 (d, $^{2}J_{CP}$=1.7 Hz, CH$_3$*C*H$_2$OP), 79.53 (*C*H$_2$NO$_2$), 128.99 (*C*H$_{Ar}$), 129.85 (*C*H$_{Ar}$), 135.44 (d, $^{3}J_{CP}$=16.0 Hz, C_{Ar}), 138.20 (C_{Ar}), 168.32 (d, $^{2}J_{CP}$=5.5 Hz, PCH*C*OOH). Anal. calcd for $C_{15}H_{22}NO_7P$: C, 50.14; H, 6.17; N, 3.90. Found: C, 50.25; H, 6.29; N, 3.77.

4.4.4. (2*R,3*R**)-2-(Diethoxyphosphoryl)-3-(4-methoxyphenyl)-4-nitrobutanoic acid (5d).** 722 mg, 77% yield, white crystals, mp 108–110 °C; IR (CCl_4): 1716, 1552, 1256, 1172, 1028 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=20.17; ^{1}H NMR (acetone-*d*): δ=1.34 (t, 3H, $^{3}J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.35 (t, 3H, $^{3}J_{HH}$=7.2 Hz, CH_3CH$_2$OP), 3.58 (dd, 1H, $^{2}J_{HP}$=19.8 Hz, $^{3}J_{HH}$=11.8 Hz, PC*H*COOH), 3.76 (s, 3H, CH_3OPh), 4.01–4.28 (m, 5H, 2×CH$_3$CH_2OP, C*H*Ar), 4.88 (dd, 1H, $^{2}J_{HH}$=12.8 Hz, $^{3}J_{HH}$=11.2 Hz, ArCHCH_AH$_B$NO$_2$), 5.30 (dd, 1H, $^{2}J_{HH}$=12.8 Hz, $^{3}J_{HH}$=4.5 Hz, ArCHCH$_A$$H_BNO_2$), 6.84 (d, 2H, $^{3}J_{HH}$=8.5 Hz, 2×CH_{Ar}), 7.32 (d, 2H, $^{3}J_{HH}$=8.5 Hz, 2×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=16.48 (d, $^{3}J_{CP}$=5.5 Hz, *C*H$_3$CH$_2$OP), 16.56 (d, $^{3}J_{CP}$=4.3 Hz, *C*H$_3$CH$_2$OP), 43.16 (d, $^{2}J_{CP}$=4.1 Hz, Ar*C*H), 49.64 (d, $^{1}J_{CP}$=126.0 Hz, P*C*HCOOH), 55.39 (CH_3OPh), 64.02 (d, $^{2}J_{CP}$=6.5 Hz, 2×CH$_3$*C*H$_2$OP), 79.67 (*C*H$_2$NO$_2$), 114.58 (*C*H$_{Ar}$), 130.24 (d, $^{3}J_{CP}$=12.8 Hz, C_{Ar}), 130.34 (*C*H$_{Ar}$), 160.16 (C_{Ar}), 168.39 (d, $^{2}J_{CP}$=5.4 Hz, PCH*C*OOH). Anal. calcd for $C_{15}H_{22}NO_8P$: C, 48.00; H, 5.91; N, 3.73. Found: C, 48.11; H, 5.83; N, 3.82.

4.4.5. (2*R,3*R**)-2-(Diethoxyphosphoryl)-3-(3,4-methylenedioxyphenyl)-4-nitrobutanoic acid (5e).** 914 mg, 94% yield, white crystals, mp 138–140 °C; IR (CCl_4): 1716, 1552, 1228, 1168, 1016 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=20.03; ^{1}H NMR (acetone-*d*): δ=1.34 (t, 3H, $^{3}J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 1.35 (t, 3H, $^{3}J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 3.58 (dd, 1H, $^{2}J_{HP}$=19.8 Hz, $^{3}J_{HH}$=11.7 Hz, PC*H*COOH), 4.00–4.28 (m, 5H, 2×CH$_3$CH_2OP, C*H*Ar), 4.88 (dd, 1H, $^{2}J_{HH}$=12.8 Hz, $^{3}J_{HH}$=11.7 Hz, ArCHCH_AH$_B$NO$_2$), 5.30 (dd, 1H, $^{2}J_{HH}$=12.8 Hz, $^{3}J_{HH}$=4.3 Hz, ArCHCH$_A$$H_BNO_2$), 5.97 (s, 2H, C$H_2O_2$Ph), 6.75 (d, 1H, $^{3}J_{HH}$=8.0 Hz, CH_{Ar}), 6.85 (dd, 1H, $^{3}J_{HH}$=8.0 Hz, $^{4}J_{HH}$=1.6 Hz, CH_{Ar}), 6.99 (d, 1H, $^{4}J_{HH}$=1.6 Hz, CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=16.47 (d, $^{3}J_{CP}$=4.0 Hz, *C*H$_3$CH$_2$OP), 16.55 (d, $^{3}J_{CP}$=5.5 Hz, *C*H$_3$CH$_2$OP), 43.70 (d, $^{2}J_{CP}$=3.9 Hz, Ar*C*H), 49.63 (d, $^{1}J_{CP}$=126.0 Hz, P*C*HCOOH), 64.05 (d, $^{2}J_{CP}$=6.6 Hz, 2×CH$_3$*C*H$_2$OP), 79.61 (*C*H$_2$NO$_2$), 102.13 (*C*H$_2$O$_2$Ph), 108.77 (*C*H$_{Ar}$), 109.13 (*C*H$_{Ar}$), 123.08 (*C*H$_{Ar}$), 132.19 (d, $^{3}J_{CP}$=16.4 Hz, C_{Ar}), 148.14 (C_{Ar}), 148.56 (C_{Ar}), 168.34 (d, $^{2}J_{CP}$=5.7 Hz, PCH*C*OOH). Anal. calcd for $C_{15}H_{20}NO_9P$: C, 46.28; H, 5.18; N, 3.60. Found: C, 46.41; H, 5.33; N, 3.72.

4.4.6. (2*R,3*R**,4*R**)-2-(Diethoxyphosphoryl)-4-nitro-3-(4-nitrophenyl)pentanoic acid (6a).** 859 mg, 85% yield, white crystals, mp 155–157 °C; IR (CCl_4): 1728, 1528, 1352, 1232, 1160, 1024, 664 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=19.42; ^{1}H NMR (acetone-*d*): δ=1.35 (t, 3H, $^{3}J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 1.35 (t, 3H, $^{3}J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 1.47 (d, 3H, $^{3}J_{HH}$=6.7 Hz, CH_3CHNO$_2$), 3.88 (dd, 1H, $^{2}J_{HP}$=21.0 Hz, $^{3}J_{HH}$=12.0 Hz, PC*H*COOH), 4.17–4.29 (m, 4H, 2×CH$_3$CH_2OP), 4.47 (ddd, 1H, $^{3}J_{HH}$=12.0, $^{3}J_{HP}$=8.2 Hz, $^{3}J_{HH}$=4.3 Hz, Ar–C*H*), 5.53 (dq, 1H, $^{3}J_{HH}$=6.7 Hz, $^{3}J_{HH}$=4.3 Hz, CH$_3$C*H*NO$_2$), 7.57 (d, 2H, $^{3}J_{HH}$=8.8 Hz, 2×CH_{Ar}), 8.21 (d, 2H, $^{3}J_{HH}$=8.8 Hz, 2×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=12.96 (*C*H$_3$CHNO$_2$), 16.47 (d, $^{3}J_{CP}$=3.4 Hz, *C*H$_3$CH$_2$OP), 16.56 (d, $^{3}J_{CP}$=3.3 Hz, *C*H$_3$CH$_2$OP), 47.79 (d, $^{1}J_{CP}$=127.9 Hz, P*C*HCOOH), 48.39 (d, $^{2}J_{CP}$=3.1 Hz, Ar*C*H), 64.02 (d, $^{2}J_{CP}$=2.7 Hz, CH$_3$*C*H$_2$OP), 64.14 (CH$_3$*C*H$_2$OP), 84.35 (CH$_3$*C*HNO$_2$), 123.96 (*C*H$_{Ar}$), 131.48 (*C*H$_{Ar}$), 143.74 (d, $^{3}J_{CP}$=16.0 Hz, C_{Ar}), 148.68 (C_{Ar}), 168.36 (d, $^{2}J_{CP}$=6.0 Hz, PCH*C*OOH). Anal. calcd for $C_{15}H_{21}N_2O_9P$: C, 44.56; H, 5.24; N, 6.93. Found: C, 44.64; H, 5.32; N, 6.80.

4.4.7. (2*R,3*R**,4*R**)-3-(4-Bromophenyl)-2-(diethoxyphosphoryl)-4-nitropentanoic acid (6b).** 975 mg, 89% yield, white crystals, mp 156–158 °C; IR (CCl_4): 1736, 1552, 1224, 1164, 1024, 664 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=19.86; ^{1}H NMR (acetone-*d*): δ=1.35 (t, 3H, $^{3}J_{HH}$=6.8 Hz, CH_3CH$_2$OP), 1.36 (t, 3H, $^{3}J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.45 (d, 3H, $^{3}J_{HH}$=6.8 Hz, CH_3CHNO$_2$), 3.77 (dd, 1H, $^{2}J_{HP}$=20.5 Hz, $^{3}J_{HH}$=12.2 Hz, PC*H*COOH), 4.17–4.29 (m, 4H, 2×CH$_3$CH_2OP), 4.34 (ddd, 1H, $^{3}J_{HH}$=12.2,

$^3J_{HP}$=8.2 Hz, $^3J_{HH}$=4.2 Hz, Ar–C*H*), 5.45 (dq, 1H, $^3J_{HH}$= 6.8 Hz, $^3J_{HH}$=4.2 Hz, CH_3CHNO_2), 7.19 (d, 2H, $^3J_{HH}$= 8.5 Hz, 2×CH_{Ar}), 7.50 (d, 2H, $^3J_{HH}$=8.5 Hz, 2×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=12.66 (CH_3CHNO_2), 16.44 (d, $^3J_{CP}$=3.0 Hz, CH_3CH_2OP), 16.54 (d, $^3J_{CP}$=2.9 Hz, CH_3CH_2OP), 47.82 (d, $^1J_{CP}$=127.9 Hz, PCHCOOH), 48.07 (d, $^2J_{CP}$=3.6 Hz, ArCH), 63.97 (d, $^2J_{CP}$=7.2 Hz, CH_3CH_2OP), 64.08 (d, $^2J_{CP}$=6.5 Hz, CH_3CH_2OP), 84.32 (d, $^3J_{CP}$=1.7 Hz, CH_3CHNO_2), 122.53 (C_{Ar}), 132.05 (CH_{Ar}), 132.08 (CH_{Ar}), 135.30 (d, $^3J_{CP}$=16.4 Hz, C_{Ar}), 168.39 (d, $^2J_{CP}$=6.0 Hz, PCHCOOH). Anal. calcd for $C_{15}H_{21}BrNO_7P$: C, 41.11; H, 4.83; N, 3.20. Found: C, 41.23; H, 4.96; N, 3.30.

4.4.8. (2*R,3*R**,4*R**)-2-(Diethoxyphosphoryl)-3-(4-methylphenyl)-4-nitropentanoic acid (6c).** 783 mg, 84% yield, white crystals, mp 148–150 °C; IR (CCl_4): 1720, 1552, 1164, 1020, 664 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=20.36; ^{1}H NMR (acetone-*d*): δ=1.36 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH_2OP), 1.37 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH_2OP), 1.42 (d, 3H, $^3J_{HH}$=6.6 Hz, CH_3CHNO_2), 2.27 (s, 3H, CH_3Ph), 3.72 (dd, 1H, $^2J_{HP}$=20.2 Hz, $^3J_{HH}$=12.3 Hz, PCHCOOH), 4.18–4.28 (m, 4H, 2×CH_3CH_2OP), 4.34 (ddd, 1H, $^3J_{HH}$=12.3 Hz, $^3J_{HP}$=8.4 Hz, $^3J_{HH}$=3.9 Hz, CHAr), 5.41 (dq, 1H, $^3J_{HH}$=6.6 Hz, $^3J_{HH}$=3.9 Hz, CH_3CHNO_2), 7.06 (s, 4H, 4×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=12.52 (CH_3CHNO_2), 16.45 (d, $^3J_{CP}$=3.3 Hz, CH_3CH_2OP), 16.55 (d, $^3J_{CP}$=3.2 Hz, CH_3CH_2OP), 20.95 (CH_3Ph), 48.09 (d, $^1J_{CP}$=127.4 Hz, PCHCOOH), 48.20 (d, $^2J_{CP}$=3.8 Hz, ArCH), 63.90 (d, $^2J_{CP}$=6.9 Hz, CH_3CH_2OP), 64.05 (d, $^2J_{CP}$=6.4 Hz, CH_3CH_2OP), 84.54 (CH_3CHNO_2), 129.59 (CH_{Ar}), 129.90 (CH_{Ar}), 132.71 (d, $^3J_{CP}$=16.4 Hz, C_{Ar}), 138.43 (C_{Ar}), 168.51 (d, $^2J_{CP}$=6.0 Hz, PCHCOOH). Anal. calcd for $C_{16}H_{24}NO_7P$: C, 51.47; H, 6.48; N, 3.75. Found: C, 51.59; H, 6.70; N, 3.67.

4.4.9. (2*R,3*R**,4*R**)-2-(Diethoxyphosphoryl)-3-(4-methoxyphenyl)-4-nitropentanoic acid (6d).** 892 mg, 92% yield, white crystals, mp 160–162 °C; IR (CCl_4): 1728, 1548, 1512, 1264, 1176, 1008, 960 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=20.61; ^{1}H NMR (acetone-*d*): δ=1.35 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH_2OP), 1.36 (t, 3H, $^3J_{HH}$=7.2 Hz, CH_3CH_2OP), 1.43 (d, 3H, $^3J_{HH}$=6.8 Hz, CH_3CHNO_2), 3.70 (dd, 1H, $^2J_{HP}$=20.2 Hz, $^3J_{HH}$=10.0 Hz, PCHCOOH), 3.76 (s, 3H, CH_3OPh), 4.17–4.28 (m, 4H, 2×CH_3CH_2OP), 4.32 (ddd, 1H, $^3J_{HH}$=12.5 Hz, $^3J_{HP}$=8.2 Hz, $^3J_{HH}$=4.0 Hz, CHAr), 5.39 (dq, 1H, $^3J_{HH}$=6.8 Hz, $^3J_{HH}$=4.0 Hz, CH_3CHNO_2), 6.84 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}), 7.12 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ= 12.59 (CH_3CHNO_2), 16.54 (d, $^3J_{CP}$=3.3 Hz, CH_3CH_2OP), 16.63 (d, $^3J_{CP}$=3.2 Hz, CH_3CH_2OP), 47.98 (d, $^2J_{CP}$= 3.6 Hz, ArCH), 48.32 (d, $^1J_{CP}$=127.0 Hz, PCHCOOH), 55.46 (CH_3OPh), 63.81 (d, $^2J_{CP}$=6.3 Hz, CH_3CH_2OP), 63.89 (d, $^2J_{CP}$=4.7 Hz, CH_3CH_2OP), 84.72 (CH_3CHNO_2), 114.34 (CH_{Ar}), 127.87 (d, $^3J_{CP}$=18.2 Hz, C_{Ar}), 131.19 (CH_{Ar}), 160.40 (C_{Ar}), 168.57 (d, $^2J_{CP}$=5.9 Hz, PCHCOOH). Anal. calcd for $C_{16}H_{24}NO_8P$: C, 49.36; H, 6.21; N, 3.60. Found: C, 49.49; H, 6.33; N, 3.67.

4.4.10. (2*R,3*R**,4*R**)-2-(Diethoxyphosphoryl)-3-(3,4-methylenedioxyphenyl)-4-nitropentanoic acid (6e).** 937 mg, 93% yield, white crystals, mp 163–166 °C; IR (CCl_4): 1736, 1552, 1224, 1040, 664 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=20.08; ^{1}H NMR (acetone-*d*): δ=1.35 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH_2OP), 1.36 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH_2OP), 1.46 (d, 3H, $^3J_{HH}$=6.6 Hz, CH_3CHNO_2), 3.68 (dd, 1H, $^2J_{HP}$=20.4 Hz, $^3J_{HH}$=12.2 Hz, PCHCOOH), 4.17–4.29 (m, 4H, 2×CH_3CH_2OP), 4.29 (ddd, 1H, $^3J_{HH}$=12.2 Hz, $^3J_{HP}$=8.6 Hz, $^3J_{HH}$=4.2 Hz, Ar–CH), 5.40 (dq, 1H, $^3J_{HH}$=6.6 Hz, $^3J_{HH}$=4.2 Hz, CH_3CHNO_2), 5.97 (s, 2H, CH_2O_2Ph), 6.65 (dd, 1H, $^3J_{HH}$=8.1 Hz, $^4J_{HH}$=1.6 Hz, CH_{Ar}), 6.75 (d, 1H, $^3J_{HH}$=8.1 Hz, CH_{Ar}), 6.76 (d, 1H, $^4J_{HH}$=1.6 Hz, CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=12.64 (CH_3CHNO_2), 16.50 (2×CH_3CH_2OP), 48.24 (d, $^1J_{CP}$=125.8 Hz, PCHCOOH), 48.31 (ArCH), 63.96 (2×CH_3CH_2OP), 84.62 (CH_3CHNO_2), 102.12 (CH_2O_2Ph), 108.59 (CH_{Ar}), 110.06 (CH_{Ar}), 123.68 (CH_{Ar}), 129.34 (d, $^3J_{CP}$=17.2 Hz, C_{Ar}), 148.28 (C_{Ar}), 156.54 (C_{Ar}), 168.44 (PCHCOOH). Anal. calcd for $C_{16}H_{22}NO_9P$: C, 47.65; H, 5.50; N, 3.47. Found: C, 47.77; H, 5.42; N, 3.56.

4.5. General procedure for the preparation of 4-aryl-3-(diethoxyphosphoryl)-1-hydroxysuccinimides 8a–e

A solution of a corresponding 4-nitrobutanoic acid **5** (1 mmol) in water (15 mL) was heated at reflux for an appropriate period of time (shown in Table 2). The resulting solution was cooled to room temperature, the solvent was evaporated and the residue was taken up in Et_2O (10 mL) and left to crystallize. Filtration of the crystals afforded pure 1-hydroxysuccinimides **8**.

4.5.1. (3*R,4*S**)-3-(Diethoxyphosphoryl)-4-(4-nitrophenyl)-1-hydroxysuccinimide (8a).** 223 mg, 60% yield, pale yellow crystals, mp 167–170 °C; IR (CCl_4): 1732, 1528, 1348, 1208, 1032 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=18.97; ^{1}H NMR (acetone-*d*): δ=1.26 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH_2OP), 1.30 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH_2OP), 3.78 (dd, 1H, $^2J_{HP}$=23.0 Hz, $^3J_{HH}$=5.2 Hz, PCHC(O)N), 4.07–4.28 (m, 4H, 2×CH_3CH_2OP), 4.50 (dd, 1H, $^3J_{HP}$=18.0 Hz, $^3J_{HH}$=5.2 Hz, ArCHC(O)N), 7.77 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}), 8.28 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=16.00 (d, $^3J_{CP}$=5.8 Hz, CH_3CH_2OP), 16.09 (d, $^3J_{CP}$=5.7 Hz, CH_3CH_2OP), 44.86 (d, $^1J_{CP}$=143.5 Hz, PCHC(O)N), 45.50 (d, $^2J_{CP}$=2.5 Hz, ArCHC(O)N), 63.43 (d, $^2J_{CP}$=6.7 Hz, CH_3CH_2OP), 64.21 (d, $^2J_{CP}$=6.4 Hz, CH_3CH_2OP), 124.14 (CH_{Ar}), 130.31 (CH_{Ar}), 143.83 (d, $^3J_{CP}$=3.0 Hz, C_{Ar}), 148.14 (C_{Ar}), 166.49 (d, $^2J_{CP}$=4.4 Hz, C(O)NOH), 170.31 (d, $^3J_{CP}$= 8.4 Hz, C(O)NOH). Anal. calcd for $C_{14}H_{17}N_2O_8P$: C, 45.17; H, 4.60; N, 7.53. Found: C, 45.30; H, 4.72; N, 7.41.

4.5.2. (3*R,4*S**)-4-(4-Bromophenyl)-3-(diethoxyphosphoryl)-1-hydroxysuccinimide (8b).** 272 mg, 67% yield, pale yellow crystals, mp 149–152 °C; IR (CCl_4): 1740, 1220, 1036 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=19.24; ^{1}H NMR (acetone-*d*): δ=1.26 (dt, 3H, $^3J_{HH}$=7.1 Hz, $^4J_{HP}$= 0.4 Hz, CH_3CH_2OP), 1.30 (dt, 3H, $^3J_{HH}$=7.0 Hz, $^4J_{HP}$= 0.5 Hz, CH_3CH_2OP), 3.63 (dd, 1H, $^2J_{HP}$=23.1 Hz, $^3J_{HH}$=4.8 Hz, PCHC(O)N), 4.05–4.26 (m, 4H, 2×CH_3CH_2OP), 4.27 (dd, 1H, $^3J_{HP}$=18.1 Hz, $^3J_{HH}$=4.8 Hz, ArCHC(O)N), 7.39 (d, 2H, $^3J_{HH}$=7.5 Hz, 2×CH_{Ar}), 7.59 (d, 2H, $^3J_{HH}$=7.5 Hz, 2×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ= 16.45 (d, $^3J_{CP}$=5.9 Hz, CH_3CH_2OP), 16.54 (d, $^3J_{CP}$=5.7 Hz, CH_3CH_2OP), 45.53 (d, $^1J_{CP}$=142.8 Hz, PCHC(O)N), 45.73 (ArCHC(O)N), 63.87 (d, $^2J_{CP}$=6.6 Hz, CH_3CH_2OP), 64.64 (d, $^2J_{CP}$=6.4 Hz, CH_3CH_2OP), 122.44 (C_{Ar}), 131.30

(CH_{Ar}), 132.70 (CH_{Ar}), 136.55 (d, $^3J_{CP}$=3.5 Hz, C_{Ar}), 167.09 (*C*(O)NOH), 171.27 (d, $^3J_{CP}$=8.4 Hz, *C*(O)NOH). Anal. calcd for $C_{14}H_{17}BrNO_6P$: C, 41.40; H, 4.22; N, 3.45. Found: C, 41.51; H, 4.31; N, 3.30.

4.5.3. (3*R,4*S**)-3-(Diethoxyphosphoryl)-4-(4-methylphenyl)-1-hydroxysuccinimide (8c).** 232 mg, 68% yield, pale yellow crystals, mp 158–161 °C; IR (CCl_4): 1720, 1512, 1356, 1216, 1032 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=18.97; ^1H NMR ($CDCl_3$): δ=1.31–141 (m, 6H, 2×CH_3CH$_2$OP), 2.35 (s, 3H, CH_3Ph), 3.51 (dd, 1H, $^2J_{HP}$=24.5 Hz, $^3J_{HH}$=4.5 Hz, PC*H*C(O)N), 4.11–4.33 (m, 5H, 2×CH$_3$CH_2OP, ArC*H*C(O)N), 7.08 (d, 2H, $^3J_{HH}$=8.0 Hz, 2×CH_{Ar}), 7.20 (d, 2H, $^3J_{HH}$=8.0 Hz, 2×CH_{Ar}); ^{13}C NMR (CH_3OD): δ=15.63 (d, $^3J_{CP}$=4.9 Hz, *C*H$_3$CH$_2$OP), 15.71 (d, $^3J_{CP}$=5.3 Hz, *C*H$_3$CH$_2$OP), 20.25 (*C*H$_3$Ph), 45.40 (d, $^1J_{CP}$=142.3 Hz, P*C*HC(O)N), 45.60 (d, $^2J_{CP}$=2.4 Hz, Ar*C*HC(O)N), 63.95 (d, $^2J_{CP}$=6.7 Hz, CH$_3$*C*H$_2$OP), 64.50 (d, $^2J_{CP}$=6.6 Hz, CH$_3$*C*H$_2$OP), 128.02 (CH_{Ar}), 129.87 (CH_{Ar}), 133.22 (d, $^3J_{CP}$=3.8 Hz, C_{Ar}), 138.52 (C_{Ar}), 167.44 (d, $^2J_{CP}$=4.4 Hz, *C*(O)NOH), 172.23 (d, $^3J_{CP}$=7.5 Hz, *C*(O)NOH). Anal. calcd for $C_{15}H_{20}NO_6P$: C, 52.79; H, 5.91; N, 4.10. Found: C, 52.71; H, 6.03; N, 3.97.

4.5.4. (3*R,4*S**)-3-(Diethoxyphosphoryl)-4-(4-methoxyphenyl)-1-hydroxysuccinimide (8d).** 228 mg, 64% yield, pale yellow crystals, mp 174–175 °C; IR (CCl_4): 1728, 1516, 1256, 1216, 1040 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=19.48; ^1H NMR (acetone-*d*): δ=1.26 (dt, 3H, $^3J_{HH}$=7.2 Hz, $^4J_{HP}$=0.5 Hz, CH_3CH$_2$OP), 1.30 (dt, 3H, $^3J_{HH}$=7.0 Hz, $^4J_{HP}$=0.5 Hz, CH_3CH$_2$OP), 3.54 (dd, 1H, $^2J_{HP}$=23.2 Hz, $^3J_{HH}$=4.5 Hz, PC*H*C(O)N), 3.80 (s, 3H, CH$_3$OPh), 4.08–4.25 (m, 5H, 2×CH$_3$CH_2OP, ArC*H*C(O)N), 6.94 (d, 2H, $^3J_{HH}$=9.0 Hz, 2×CH_{Ar}), 7.30 (d, 2H, $^3J_{HH}$=9.0 Hz, 2×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=16.79 (d, $^3J_{CP}$=5.6 Hz, *C*H$_3$CH$_2$OP), 16.88 (d, $^3J_{CP}$=5.3 Hz, *C*H$_3$CH$_2$OP), 45.98 (Ar*C*HC(O)N), 46.33 (d, $^1J_{CP}$=141.5 Hz, P*C*HC(O)N), 55.90 (*C*H$_3$OPh), 64.13 (d, $^2J_{CP}$=6.7 Hz, CH$_3$*C*H$_2$OP), 64.86 (d, $^2J_{CP}$=6.4 Hz, CH$_3$*C*H$_2$OP), 115.40 (CH_{Ar}), 129.50 (C_{Ar}), 130.48 (CH_{Ar}), 160.74 (C_{Ar}), 167.64 (d, $^2J_{CP}$=4.7 Hz, *C*(O)NOH), 172.17 (d, $^3J_{CP}$=7.4 Hz, *C*(O)NOH). Anal. calcd for $C_{15}H_{20}NO_7P$: C, 50.42; H, 5.64; N, 3.92. Found: C, 50.51; H, 5.75; N, 3.82.

4.5.5. (3*R,4*S**)-3-(Diethoxyphosphoryl)-4-(3,4-methylenedioxyphenyl)-1-hydroxysuccinimide (8e).** 293 mg, 79% yield, pale yellow crystals, mp 210–211 °C; IR (CCl_4): 1724, 1504, 1256, 1220, 1032 cm^{-1}; ^{31}P NMR (acetone-*d*): δ=19.42; ^1H NMR (acetone-*d*): δ=1.26 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.30 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 3.55 (dd, 1H, $^2J_{HP}$=23.0 Hz, $^3J_{HH}$=4.8 Hz, PC*H*C(O)N), 4.06–4.26 (m, 5H, 2×CH$_3$CH_2OP, ArC*H*C(O)N), 6.02 (s, 2H, CH_2O$_2$Ph), 6.83–6.93 (m, 3H, 3×CH_{Ar}); ^{13}C NMR (acetone-*d*): δ=16.55 (2×*C*H$_3$CH$_2$OP), 46.04 (d, $^1J_{CP}$=143.2 Hz, P*C*HC(O)N), 46.12 (Ar*C*HC(O)N), 63.75 (CH$_3$*C*H$_2$OP), 64.86 (CH$_3$*C*H$_2$OP), 102.16 (*C*H$_2$O$_2$Ph), 109.08 (CH_{Ar}), 109.69 (CH_{Ar}), 122.77 (CH_{Ar}), 123.46 (C_{Ar}), 130.87 (C_{Ar}), 148.42 (C_{Ar}), 167.25 (d, $^2J_{CP}$=5.9 Hz, *C*(O)NOH), 171.57 (d, $^3J_{CP}$=6.9 Hz, *C*(O)NOH). Anal. calcd for $C_{15}H_{18}NO_8P$: C, 48.52; H, 4.89; N, 3.77. Found: C, 48.62; H, 5.00; N, 3.70.

4.6. General procedure for the preparation of dicyclohexylammonium 3-aryl-2-(diethoxyphosphoryl)-4-oxopentanoates 10a–e

A solution of 4-nitropentanoic acid **6** (1 mmol) in water (15 mL) was heated at reflux for an appropriate period of time (shown in Table 2). The resulting solution was cooled to room temperature and the solvent was evaporated. The residue was dissolved in CH_2Cl_2 (10 mL) and dicyclohexylamine (1 mmol, 181 mg) was added. The solvent was evaporated off and the residue was taken up in Et_2O (10 mL) and left to crystallize. Filtration of the crystals afforded pure 4-oxopentanoates **10**.

4.6.1. Dicyclohexylammonium (2*R,3*S**)-2-(diethoxyphosphoryl)-3-(4-nitrophenyl)-4-oxopentanoate (10a).** 388 mg, 70% yield, pale yellow crystals, mp 163–165 °C; IR (CCl_4): 2936, 1712, 1512, 1344, 1240, 1056, 1032, 968 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=25.56; ^1H NMR ($CDCl_3$): δ=0.97 (t, 3H, $^3J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 1.11 (t, 3H, $^3J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 1.16–1.38 (m, 6H, 3×CH_2(*c*Hex)), 1.40–1.90 (m, 10H, 5×CH_2(*c*Hex)), 1.98–2.35 (m, 4H, 2×CH_2(*c*Hex)), 2.13 (s, 3H, CH_3CO), 2.98–3.07 (m, 2H, 2×C*H*(*c*Hex)), 3.65 (dd, 1H, $^2J_{HP}$=20.6 Hz, $^3J_{HH}$=11.8 Hz, PC*H*COO$^-$), 3.67–4.12 (m, 4H, 2×CH$_3$CH_2OP), 4.70 (dd, 1H, $^3J_{HH}$=11.8 Hz, $^3J_{HP}$=8.5 Hz, ArC*H*), 7.54 (d, 2H, $^3J_{HH}$=8.7 Hz, 2×CH_{Ar}), 8.16 (d, 2H, $^3J_{HH}$=8.7 Hz, 2×CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ=15.66 (d, $^3J_{CP}$=6.7 Hz, *C*H$_3$CH$_2$OP), 15.78 (d, $^3J_{CP}$=7.9 Hz, *C*H$_3$CH$_2$OP), 24.56 (*C*H$_2$(*c*Hex)), 24.80 (*C*H$_2$(*c*Hex)), 28.50 (*C*H$_2$(*c*Hex)), 29.34 (*C*H$_3$CO), 51.68 (d, $^1J_{CP}$=126.0 Hz, P*C*HCOO$^-$), 52.21 (Ar*C*H), 57.48 (*C*H(*c*Hex)), 60.76 (d, $^2J_{CP}$=6.8 Hz, CH$_3$*C*H$_2$OP), 61.85 (d, $^2J_{CP}$=6.2 Hz, CH$_3$*C*H$_2$OP), 123.08 (CH_{Ar}), 130.02 (CH_{Ar}), 143.80 (C_{Ar}), 146.87 (C_{Ar}), 170.10 (PCH*C*OO$^-$), 205.08 (d, $^3J_{CP}$=18.2 Hz, CH$_3$*C*O). Anal. calcd for $C_{27}H_{43}N_2O_8P$: C, 58.47; H, 7.81; N, 5.05. Found: C, 58.61; H, 7.73; N, 5.15.

4.6.2. Dicyclohexylammonium (2*R,3*S**)-3-(4-bromophenyl)-2-(diethoxyphosphoryl)-4-oxopentanoate (10b).** 329 mg, 56% yield, white crystals, mp 155–157 °C; IR (CCl_4): 2936, 1712, 1636, 1356, 1240, 1056, 1032, 968 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=26.04; ^1H NMR ($CDCl_3$): δ=0.97 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.12 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.18–1.34 (m, 6H, 3×CH_2(*c*Hex)), 1.39–1.58 (m, 4H, 2×CH_2(*c*Hex)), 1.60–1.70 (m, 2H, CH_2(*c*Hex)), 1.74–1.88 (m, 4H, 2×CH_2(*c*Hex)), 1.95–2.07 (m, 4H, 2×CH_2(*c*Hex)), 2.08 (s, 3H, CH_3CO), 2.94–3.04 (m, 2H, 2×C*H*(*c*Hex)), 3.57 (dd, 1H, $^2J_{HP}$=20.6 Hz, $^3J_{HH}$=11.8 Hz, PC*H*COO$^-$), 3.59–4.11 (m, 4H, 2×CH$_3$CH_2OP), 4.53 (dd, 1H, $^3J_{HH}$=11.8 Hz, $^3J_{HP}$=8.6 Hz, ArC*H*), 7.22 (d, 2H, $^3J_{HH}$=8.5 Hz, 2×CH_{Ar}), 7.41 (d, 2H, $^3J_{HH}$=8.5 Hz, 2×CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ=15.70 (d, $^3J_{CP}$=7.3 Hz, *C*H$_3$CH$_2$OP), 15.82 (d, $^3J_{CP}$=7.7 Hz, *C*H$_3$CH$_2$OP), 24.66 (*C*H$_2$(*c*Hex)), 24.91 (*C*H$_2$(*c*Hex)), 28.59 (*C*H$_2$(*c*Hex)), 29.02 (*C*H$_3$CO), 51.53 (d, $^1J_{CP}$=127.4 Hz, P*C*HCOO$^-$), 52.51 (Ar*C*H), 57.24 (*C*H(*c*Hex)), 60.63 (d, $^2J_{CP}$=6.6 Hz, CH$_3$*C*H$_2$OP), 61.80 (d, $^2J_{CP}$=6.6 Hz, CH$_3$*C*H$_2$OP), 121.04 (C_{Ar}), 130.96 (CH_{Ar}), 131.17 (CH_{Ar}), 135.21 (C_{Ar}), 170.65 (d, $^2J_{CP}$=3.8 Hz, PCH*C*OO$^-$), 205.72 (d, $^3J_{CP}$=18.2 Hz, CH$_3$*C*O). Anal. calcd for $C_{27}H_{43}BrNO_6P$: C, 55.10; H, 7.36; N, 2.38. Found: C, 55.01; H, 7.23; N, 2.27.

4.6.3. Dicyclohexylammonium (2*R,3*S**)-2-(diethoxyphosphoryl)-3-(4-methylphenyl)-4-oxopentanoate (10c).** 261 mg, 50% yield, white crystals, mp 122–124 °C; IR (CCl_4): 2936, 1720, 1512, 1356, 1248, 1032, 968, 664 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=26.33; ^1H NMR ($CDCl_3$): δ=0.96 (t, 3H, $^3J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 1.10 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.19–1.35 (m, 6H, 3×CH_2(*c*Hex)), 1.41–1.68 (m, 6H, 3×CH_2(*c*Hex)), 1.76–1.86 (m, 4H, 2×CH_2(*c*Hex)), 1.98–2.03 (m, 4H, 2×CH_2(*c*Hex)), 2.06 (s, 3H, CH_3CO), 2.30 (s, 3H, CH_3Ph), 2.95–3.04 (m, 2H, 2×C*H*(*c*Hex)), 3.62 (dd, 1H, $^2J_{HP}$=20.8 Hz, $^3J_{HH}$=11.3 Hz, PC*H*COO$^-$), 3.55–4.11 (m, 4H, 2×CH$_3$CH_2OP), 4.50 (dd, 1H, $^3J_{HH}$=11.3 Hz, $^3J_{HP}$=9.1 Hz, ArC*H*), 7.08 (d, 2H, $^3J_{HH}$=7.5 Hz, 2×CH_{Ar}), 7.22 (d, 2H, $^3J_{HH}$=7.5 Hz, 2×CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ=15.60 (d, $^3J_{CP}$=6.6 Hz, *C*H$_3$CH$_2$OP), 15.75 (d, $^3J_{CP}$=7.1 Hz, *C*H$_3$CH$_2$OP), 20.71 (*C*H$_3$Ph), 24.62 (*C*H$_2$(*c*Hex)), 24.84 (*C*H$_2$(*c*Hex)), 28.56 (*C*H$_2$(*c*Hex)), 28.78 (*C*H$_3$CO), 51.40 (d, $^1J_{CP}$=127.2 Hz, P*C*HCOO$^-$), 52.19 (Ar*C*H), 57.44 (*C*H(*c*Hex)), 60.64 (d, $^2J_{CP}$=6.7 Hz, CH$_3$*C*H$_2$OP), 61.66 (d, $^2J_{CP}$=6.6 Hz, CH$_3$*C*H$_2$OP), 128.76 (*C*H$_{Ar}$), 129.10 (*C*H$_{Ar}$), 132.84 (*C*$_{Ar}$), 136.54 (*C*$_{Ar}$), 171.13 (d, $^2J_{CP}$=3.8 Hz, PCH*C*OO$^-$), 206.13 (d, $^3J_{CP}$=19.3 Hz, CH$_3$*C*O). Anal. calcd for $C_{28}H_{46}NO_6P$: C, 64.22; H, 8.85; N, 2.67. Found: C, 64.34; H, 8.96; N, 2.77.

4.6.4. Dicyclohexylammonium 2-(diethoxyphosphoryl)-3-(4-methoxyphenyl)-4-oxopentanoate (10d). 333 mg, 62% yield, white crystals, mp 136–138 °C; IR (CCl_4): 2936, 1716, 1512, 1356, 1248, 1032 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=26.30, 26.71 (81:19); (2*R**,3*S**)-**10d**: ^{31}P NMR ($CDCl_3$): δ=26.30; ^1H NMR ($CDCl_3$): δ=0.98 (t, 3H, $^3J_{HH}$=7.0 Hz, CH_3CH$_2$OP), 1.12 (t, 3H, $^3J_{HH}$=7.2 Hz, CH_3CH$_2$OP), 1.18–1.34 (m, 6H, 3×CH_2(*c*Hex)), 1.40–1.67 (m, 6H, 3×CH_2(*c*Hex)), 1.76–1.86 (m, 4H, 2×CH_2(*c*Hex)), 1.97–2.04 (m, 4H, 2×CH_2(*c*Hex)), 2.05 (s, 3H, CH_3CO), 2.91–3.04 (m, 2H, 2×C*H*(*c*Hex)), 3.60 (dd, 1H, $^2J_{HP}$=20.8 Hz, $^3J_{HH}$=11.8 Hz, PC*H*COO$^-$), 3.55–4.20 (m, 4H, 2×CH$_3$CH_2OP), 3.78 (s, 3H, CH_3OPh), 4.49 (dd, 1H, $^3J_{HH}$=11.8 Hz, $^3J_{HP}$=8.8 Hz, ArC*H*), 6.82 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}), 7.24 (d, 2H, $^3J_{HH}$=8.8 Hz, 2×CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ=15.75 (d, $^3J_{CP}$=5.5 Hz, *C*H$_3$CH$_2$OP), 15.84 (d, $^3J_{CP}$=6.2 Hz, *C*H$_3$CH$_2$OP), 24.65 (*C*H$_2$(*c*Hex)), 24.88 (*C*H$_2$(*c*Hex)), 28.59 (*C*H$_2$(*c*Hex)), 28.76 (*C*H$_3$CO), 51.48 (d, $^1J_{CP}$=127.3 Hz, P*C*HCOO$^-$), 52.17 (Ar*C*H), 54.97 (*C*H$_3$OPh), 57.01 (*C*H(*c*Hex)), 60.61 (d, $^2J_{CP}$=6.7 Hz, CH$_3$*C*H$_2$OP), 61.56 (d, $^2J_{CP}$=7.5 Hz, CH$_3$*C*H$_2$OP), 113.57 (*C*H$_{Ar}$), 127.98 (*C*$_{Ar}$), 130.29 (*C*H$_{Ar}$), 158.36 (*C*$_{Ar}$), 171.12 (d, $^2J_{CP}$=3.8 Hz, PCH*C*OO$^-$), 206.17 (d, $^3J_{CP}$=19.2 Hz, CH$_3$*C*O). Anal. calcd for $C_{28}H_{46}NO_7P$: C, 62.32; H, 8.59; N, 2.60. Found: C, 62.33; H, 8.70; N, 2.47.

4.6.5. Dicyclohexylammonium 2-(diethoxyphosphoryl)-3-(3,4-methylenedioxyphenyl)-4-oxopentanoate (10e). 326 mg, 59% yield, pale yellow crystals, mp 144–146 °C; IR (CCl_4): 2936, 1712, 1612, 1484, 1352, 1240, 1040, 968 cm^{-1}; ^{31}P NMR ($CDCl_3$): δ=26.36, 26.76 (86:14); (2*R**,3*S**)-**10e**: ^{31}P NMR ($CDCl_3$): δ=26.36; ^1H NMR ($CDCl_3$): δ=1.02 (t, 3H, $^3J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 1.14 (t, 3H, $^3J_{HH}$=7.1 Hz, CH_3CH$_2$OP), 1.21–1.36 (m, 6H, 3×CH_2(*c*Hex)), 1.41–1.53 (m, 4H, 2×CH_2(*c*Hex)), 1.60–1.68 (m, 2H, CH_2(*c*Hex)), 1.75–1.85 (m, 4H, 2×CH_2(*c*Hex)), 1.95–2.06 (m, 4H, 2×CH_2(*c*Hex)), 2.08 (s, 3H, CH_3CO), 2.87–3.02 (m, 2H, 2×C*H*(*c*Hex)), 3.55 (dd, 1H, $^2J_{HP}$=20.6 Hz, $^3J_{HH}$=11.7 Hz, PC*H*COO$^-$), 3.64–4.13 (m, 4H, 2×CH$_3$CH_2OP), 4.47 (dd, 1H, $^3J_{HH}$=11.7 Hz, $^3J_{HP}$=8.8 Hz, ArC*H*), 5.91 (s, 2H, CH_2OPh), 6.73 (d, 1H, $^3J_{HH}$=8.0 Hz, CH_{Ar}), 6.81 (s, 1H, CH_{Ar}), 6.83 (d, 1H, $^3J_{HH}$=8.0 Hz, CH_{Ar}); ^{13}C NMR ($CDCl_3$): δ=15.61 (d, $^3J_{CP}$=3.6 Hz, *C*H$_3$CH$_2$OP), 15.71 (d, $^3J_{CP}$=4.0 Hz, *C*H$_3$CH$_2$OP), 24.51 (*C*H$_2$(*c*Hex)), 24.75 (*C*H$_2$(*c*Hex)), 28.44 (*C*H$_2$(*c*Hex)), 28.62 (*C*H$_3$CO), 51.39 (d, $^1J_{CP}$=127.2 Hz, P*C*HCOO$^-$), 52.01 (Ar*C*H), 57.21 (*C*H(*c*Hex)), 60.44 (d, $^2J_{CP}$=6.5 Hz, CH$_3$*C*H$_2$OP), 61.50 (d, $^2J_{CP}$=6.5 Hz, CH$_3$*C*H$_2$OP), 100.52 (*C*H$_2$O$_2$Ph), 107.70 (*C*H$_{Ar}$), 109.12 (*C*H$_{Ar}$), 122.72 (*C*H$_{Ar}$), 129.57 (*C*$_{Ar}$), 146.45 (*C*$_{Ar}$), 147.15 (*C*$_{Ar}$), 170.75 (d, $^2J_{CP}$=3.8 Hz, PCH*C*OO$^-$), 205.85 (d, $^3J_{CP}$=19.6 Hz, CH$_3$*C*O). Anal. calcd for $C_{28}H_{44}NO_8P$: C, 60.75; H, 8.01; N, 2.53. Found: C, 60.87; H, 8.13; N, 2.45.

4.7. X-ray single crystal structure analysis for 8b

Formula: $C_{14}H_{17}NO_6PBr$, M_w=406.20, pale yellow crystal 0.40×0.30×0.20 mm, a=8.3309(4), b=10.0423(4), c=11.7799(4) Å, α=74.941(4), β=76.686(4), γ=65.860(4)°, V=859.81(6) Å^3, ρ_{calc}=1.569 g cm^{-3}, μ=2.51 cm^{-1}, Z=2, crystal system: triclinic, space group: P-1, λ=0.71073 Å, T=293 K, ω scans, 8916 reflections collected ($\pm h$,$\pm k$,$\pm l$), $2\theta_{max}$=50°, 2932 unique reflections (R_{int}=0.021) and 2406 observed reflections [$I \geq 2\sigma(I)$], 239 refined parameters, refinement on F^2, R_{all}=0.059, $wR(F^2)$=0.145, max. and min. residual electron density ($\Delta\rho_{max}$=0.88 and $\Delta\rho_{min}$=−0.85) eÅ^{-3}—both peaks located near Br atom, X-ray data were collected with Kuma Diffraction KM4 CCD area detector diffractometer. Structure was solved by direct methods and refined by full matrix least-squares—SHELXTL.[26]

Crystallographic data (excluding structure factors) for the structure reported herein, have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication CCDC 605788. Copies of the data can be obtained free of charge on application to The Director, CCDC, 12 Union Road, Cambridge CB2 1EZ, UK. Any request should be accompanied by a full literature citation.

Acknowledgements

This work was financed by the Ministry of Education and Science (Project No. 3 T09A 075 28, to H.K. and Ł.A.) and the Institute of General and Ecological Chemistry (J.W. and W.M.W.). Ł.A. is a grant holder of 'Mechanizm WIDDOK' program supported by European Social Fund and Polish State (contract number Z/2.10/II/2.6/04/05/U/2/06).

References and notes

1. Noland, W. E. *Chem. Rev.* **1955**, *55*, 137–155.
2. Pinnick, H. W. *Org. React.* **1990**, *38*, 655–791.
3. Ballini, R.; Petrini, M. *Tetrahedron* **2004**, *60*, 1017–1047.
4. Krawczyk, H.; Wolf, W. M.; Śliwiński, M. *J. Chem. Soc., Perkin Trans. 1* **2002**, 2794–2798.
5. Moonen, K.; Laureyn, I.; Stevens, C. V. *Chem. Rev.* **2004**, *104*, 6177–6215.

6. Truel, I.; Mohamed-Hachi, A.; About-Jaudet, E.; Collignon, N. *Synth. Commun.* **1997**, 1165–1172.
7. Touil, S.; Zantour, H. *Phosphorus Sulfur Silicon Relat. Elem.* **1997**, 183–190.
8. Kraus, G. A.; Choudhury, P. K. *Org. Lett.* **2002**, 2033–2034.
9. Kraus, G. A.; Choudhury, P. K. *Eur. J. Org. Chem.* **2004**, 2193–2197.
10. Błaszczyk, E.; Krawczyk, H.; Janecki, T. *Synlett* **2004**, 2685–2688.
11. Villiéras, J.; Rambaud, M. *Synthesis* **1984**, 406–408.
12. Minami, T.; Hirakawa, K.; Koyanagi, S.; Nakamura, S.; Yamaguchi, M. *J. Chem. Soc., Perkin Trans. 1* **1990**, 2385–2390.
13. Lee, K.; Jackson, J. A.; Wiemer, D. F. *J. Org. Chem.* **1993**, *58*, 5967–5971.
14. Janecki, T.; Błaszczyk, E. *Synthesis* **2001**, 403–408.
15. Janecki, T.; Błaszczyk, E. *Tetrahedron Lett.* **2001**, *42*, 2919–2922.
16. Krawczyk, H.; Wąsek, K.; Kędzia, J. *Synlett* **2005**, 2648–2652.
17. Krawczyk, H.; Albrecht, Ł. *Synthesis* **2005**, 2887–2896.
18. Wright, S. W.; Hageman, D. L.; Wright, A. S.; McClure, L. D. *Tetrahedron Lett.* **1997**, *38*, 7345–7348.
19. Adiwidjaja, G.; Meyer, B.; Thiem, J. Z. *Naturforsch.* **1979**, 1547–1551.
20. Benezra, C. *J. Am. Chem. Soc.* **1973**, *95*, 6890–6894.
21. Bentrude, W. G.; Setzer, W. N. *Phosphorus-31 NMR Spectroscopy in Stereochemical Analysis*; Verkade, J. G., Quin, L. D., Eds.; VCH: Deerfield, 1987; Chapter 11.
22. Piotowska, D. G.; Wróblewski, A. E. *Tetrahedron* **2003**, *59*, 8405–8410.
23. Krawczyk, H.; Albrecht, Ł.; Wojciechowski, J.; Wolf, W. M. *Acta Crystallogr., Sect. E* **2006**, *62*, o2743–o2745.
24. Jones, P. G. *Acta Crystallogr., Sect. E* **2003**, *59*, o1951–o1952.
25. Allen, F. H.; Kennard, O.; Watson, D. G.; Brammer, L.; Orpen, A. G.; Taylor, R. Typical Interatomic Distances: Organic Compounds. In *International Tables for Crystallography*; Wilson, A. J. C., Ed.; Kluwer: Dordrecht, 1992; Vol. C, pp 685–705.
26. Sheldrick, G. M. *SHELXTL, Version 6.12*; Bruker AXS: Madison, Wisconsin, WI, 2001.