Phosphonic Systems. Part 3.[1] Diethyl Prop-2-enylphosphonate, a New and Versatile Substrate in Carbon–Carbon Bond Formation

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The reactions of lithiated diethyl prop-2-enylphosphonate with α,β-unsaturated ketones and carboxylic esters are described. In simple cases the conjugate addition of the lithium phosphonate *via* its α- or γ-carbon atom has been observed. In most cases, however, the phosphonate salt has been shown to act as a γ-donor, and a β-acceptor, yielding, in a sequence of reactions, carbocyclic products containing two (or three) new carbon–carbon bonds.

The scope of synthetic applications of phosphoryl-stabilized anions is immense;[2] among various phosphoryl substrates the esters of alk-2-enyl (allylic) phosphonic acids occupy an important position. In the majority of cases, however, the carbanionic centre developed upon metallation is additionally stabilized by a group in the γ-position, hence the substrates represent vinylogues of the typical β-substituted phosphonates.

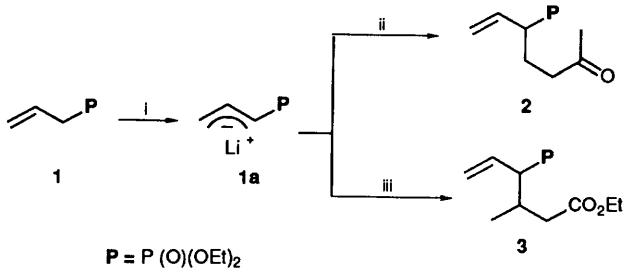
Alk-2-enylphosphonic esters activated in position γ by alkoxycarbonyl,[3] aryl,[4] cyano[5] or XR (X = O,S)[6] groups have found wide applications in the synthesis of olefins *via* the usual reactions with aldehydes, followed by phosphate elimination. Among the reactions between aldehydes and the allylic phosphonates containing no additional stabilizing groups, notable examples are the syntheses of β-carotenes from retinylphosphonate,[7] or the preparation of other polyenic systems from alka-2,4-dienylphosphonates.[8] In another approach involving α-reactivity of the lithiated alkenylphosphonates, *E*-olefins were prepared by alkylation of a substrate followed by reduction of the α-substituted alk-2-enylphosphonate.[9] It was reported[10] that, in reactions with α,β-unsaturated carbonyl compounds, phosphoryl-stabilized anions led to both olefin formation (addition to the carbonyl carbon) and Michael addition (addition across the double bond), depending upon substrates and reaction conditions.

It has been shown by us[1] and by other workers[11] that lithiated diethyl prop-2-enylphosphonate **1** behaves as an ambident nucleophile in reactions with a variety of electrophilic reagents, yielding 1-substituted prop-2-enyl- as well as 3-substituted prop-1-enyl-phosphonates. When treated with EtONa in EtOH, the phosphonate **1** undergoes prototropic isomerization to the prop-1-enyl derivative, which reacts rapidly with ethoxide ion according to the conjugate addition mechanism, giving diethyl 2-ethoxypropylphosphonate as the final product.[1] Those results led us to expect the phosphonate **1** to behave, under suitable conditions, as a versatile substrate capable of offering, in a tandem reaction, its α- (or γ-) *and* β-carbon atoms as the nucleophilic and electrophilic centres, respectively. In this paper we report the preliminary results of our study of such multicentred reactivity of the lithiated phosphonate **1** with α,β-unsaturated carbonyl compounds.

Results and Discussion

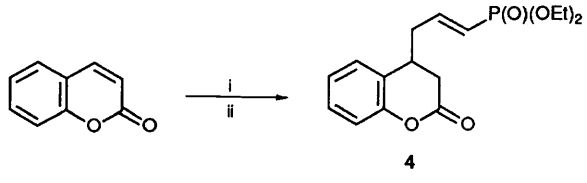
The lithium salt **1a** of compound **1** reacts smoothly with α,β-unsaturated ketones and esters, but the course of the reaction is a sensitive function of the carbonyl substrate's structure. In all cases high selectivity was observed and a single phosphorus-containing product was usually obtained in each reaction. The reactions can be grouped into the following general types.

Simple Nucleophilic Addition.—When the lithium derivative **1a** was allowed to react with but-3-en-2-one or ethyl but-2-enoate, conjugate addition of the anion **1a** *via* its α-carbon atom occurred, without any evidence for attack at the carbonyl centre (Scheme 1). The structure of the products was unambiguously



Scheme 1 *Reagents:* i, BuLi; ii, but-3-en-2-one, then H_3O^+; iii, ethyl but-2-enoate, then H_3O^+

determined by NMR (^1H, ^{13}C, ^{31}P) spectroscopy. The absence of any isomeric adducts formed by the addition of anion **1a** *via* the γ-carbon was easily demonstrated in the ^{31}P NMR spectra of the reaction products, as the phosphorus chemical shifts for the allylic and vinylic phosphonates differ by *ca.* 10 ppm.

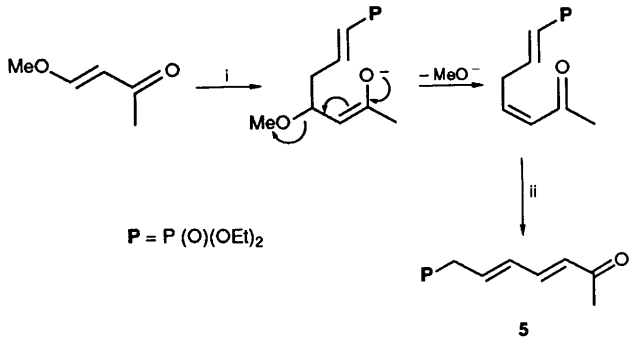


Scheme 2 *Reagents:* **1a**, then H_3O^+

Triester **3** was formed as a *ca.* 1:1 diastereoisomeric mixture, the composition of which did not depend on the configurational purity of the starting crotonate.

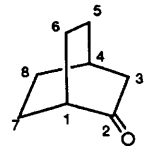
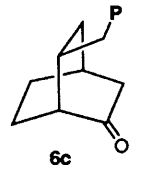
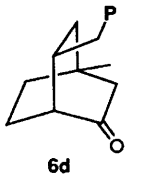
When a configurationally constrained (*Z*) unsaturated ester (coumarin) was used as substrate, the addition occurred exclusively *via* the γ-carbon of anion **1a** (Scheme 2). The position of the olefinic bond in the product **4** was confirmed (in addition to the characteristic ^{31}P chemical shift of δ_P 14.5) by ^{13}C NMR spectroscopy. The proton noise-decoupled ^{13}C spectrum showed two signals (δ_C 121.4, 148.1) in the sp^2-carbon range other than the signals of aromatic carbons, and those two signals showed J_{CP} couplings of 186.8 and 5.5 Hz, respectively.

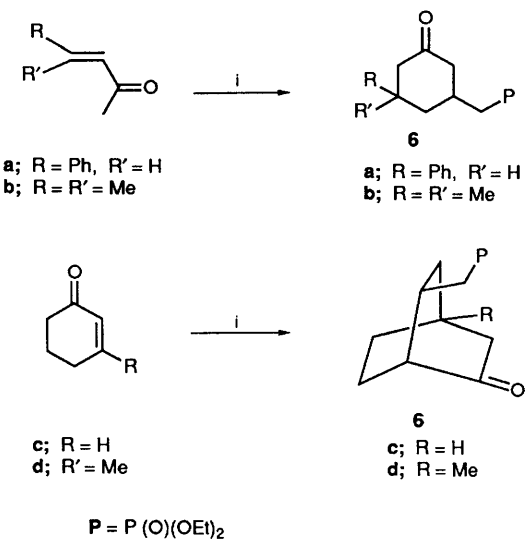
Addition–Elimination.—γ-Nucleophilicity of the anion **1a** was also displayed in the reaction with (*E*)-4-methoxybut-3-en-2-one, but the addition in this case was accompanied by expulsion of the methoxide ion, followed by isomerization to the fully conjugated keto phosphonate **5** (Scheme 3). Again, the structure



Scheme 3 *Reagents:* i, **1a**; ii, base, then H_3O^+

Table 1 Carbon-13 shieldings (δ_C) in bicyclo[2.2.2]octan-2-ones

Compound	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8
	42.2	216.8	44.6	27.8	24.7	23.3	23.3	24.7
 **6c**	48.9	208.8	44.9	28.0	34.2	31.3	23.0	23.2
 **6d**	48.3	215.7	50.4	32.6	40.9	31.1	30.2	23.2



Scheme 4 *Reagents:* **1a**, then H_3O^+

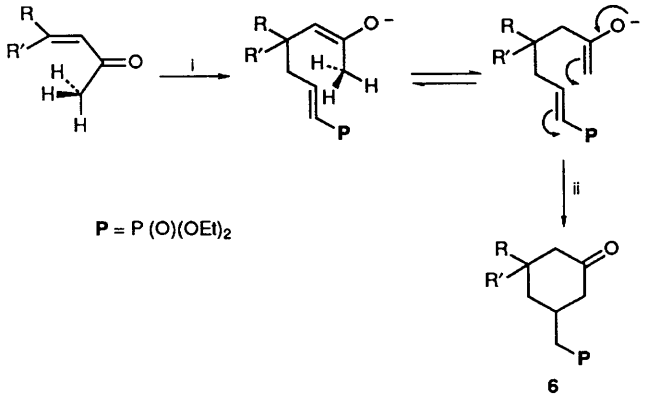
of the product **5** was unambiguously confirmed by ^1H, ^{13}C, ^{31}P (δ_P 22.9) NMR, as well as IR spectroscopy. It is interesting to note that the initial adduct (Scheme 3) showed a preference for the elimination of methoxide ion rather than for intramolecular attack at the β-carbon atom of the phosphonate to yield the dihydropyran or cyclohexane (*vide infra*) derivative. A similar attack by oxygen at the vinylic carbon, yielding a substituted dihydrofuran, was reported[12] for the reaction of the carbanion derived from diethyl 3-chlorobut-2-enylphosphonate with benzaldehyde. The isomerization to the final product **5** is driven by the tendency to extend the conjugated system, and also demonstrates the known[13] preference of the olefinic bond in alkenylphosphonic esters to move away (to the β,γ rather than the α,β position) from the phosphorus atom.

Multiple Addition.—In the following group of reactions it was found that the phosphonate **1** can behave as a nucleophilic/electrophilic reagent giving, in a tandem reaction, a product containing two new carbon–carbon bonds. When the salt **1a** was allowed to react with β-substituted (cyclic and acyclic) α,β-unsaturated ketones containing an enolizable α′ hydrogen and no leaving group in position β, the reaction resulted in annulation to afford a cyclohexanone derivative (Scheme 4). The structure of products **6a–d** was unequivocally confirmed by NMR spectroscopy. ^1H and ^{13}C NMR spectra demonstrated complete disappearance of olefinic hydrogen (and carbon) atoms. For products **6a** and **6b** the absence of the acetyl methyl signal (singlet, δ_H ~2) indicated the involvement of that methyl group in skeleton formation. The exocyclic location of the carbon atom attached to phosphorus was demonstrated for all products in the ^1H-coupled ^{13}C NMR spectra. The same spectra provided, for each compound, information on the number of carbon atoms bonded to three, two, one or no hydrogen atoms. Double-resonance experiments were used to determine the connectivity between scalar coupled protons. The results from these experiments enabled complete proton assignments to be made. The sequence of the carbon atoms was then determined from the connectivities in the heteronuclear 2D spectra. Double-resonance experiments and the coupling constants determined offered an insight into the stereochemistry of products **6**. For example, in 3-(diethoxyphosphorylmethyl)-5-phenylcyclohexanone **6a**, $J_{5,4a}$ = 8.6 Hz and $J_{5,4e}$ = 3.9 Hz; hence 5-H is axial, *i.e.* the phenyl group occupies the equatorial position. The position of the CH_2P substituent is more ambiguous, as the constant $J_{3,2a}$ is 5.4 Hz, and the value of $J_{3,2e}$ could not be determined. Since compound **6a** was obtained as a single diastereoisomer, it is likely that the substituent at C-3 is also equatorial, *i.e.* the geometry of the compound is *cis*. In 3-(diethoxyphosphorylmethyl)-5,5-dimethylcyclohexanone **6b** the CH_2P group was found to have the equatorial orientation. The 3-H atom (identified in a two-dimensional heteronuclear ^1H–^{13}C spectrum as correlating with the single methine carbon in the molecule) was shown to be axial, as indicated by the following spin–spin coupling constants: $J_{3,2a}$ 11.0 Hz; $J_{3,2e}$ 5.8 Hz; $J_{3,4a}$ 12.4 Hz; $J_{3,4e}$ 5.5 Hz.

The structure of the bicyclic products **6c** and **6d** was also confirmed by NMR spectroscopy, including double-resonance, DEPT, ^1H-coupled ^{13}C and heteronuclear 2D spectra. The ^{13}C NMR data could be compared with those reported[14] for bicyclo[2.2.2]octan-2-one (Table 1). It is clear that, after accounting for the effect of the phosphonomethyl substituent, the ^{13}C NMR spectra of products **6c** and **6d** correspond closely to that for the parent bicyclic ketone, and therefore provide evidence for the structure of the carbon skeletons of the products. The configuration at C-6 (*syn*-orientation of the phosphonomethyl group and the carbonyl oxygen) was determined as follows. For compound **6d**, hydrogen atoms of the C-5 methylene group resonate at δ_H 1.74 and 1.00. The latter signal appears as a doublet of doublet of doublets, with coupling constants 13.7 (geminal), 5.9 (vicinal) and 2.8 (long-range, W-coupling) Hz, respectively. The value of the vicinal coupling indicates a dihedral angle of 120° (as opposed to 0°), and hence a *syn* relationship between this 5-H and the CH_2P group. The long-range coupling, observed clearly in the COSY spectrum

of compound **6d**, was taken as evidence for a planar, zigzag W-orientation between the 5-H in question and the *syn*-8-H atom.[15] The 'W'-orientation is only possible for a *syn*-5-H; the information which, in turn, helped us to establish the configuration at C-6. Analogous results were obtained for compound **6c**; it was therefore concluded that the configuration of that product is the same as for compound **6d**.

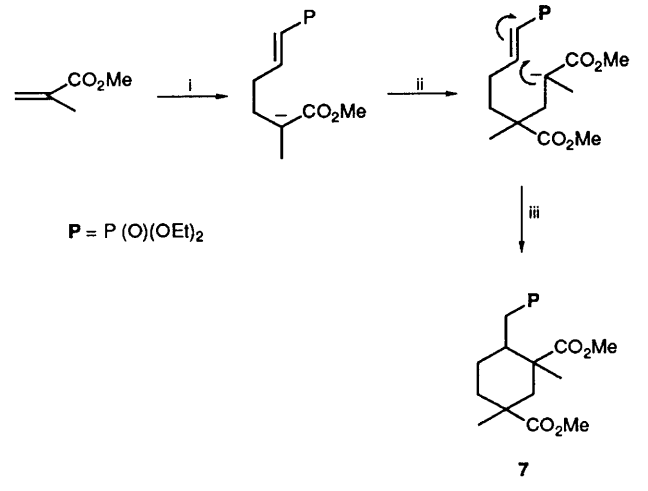
The transformations presented in Scheme 4 can be explained by a sequence of reactions involving (i) conjugate addition *via* the γ-carbon of the salt **1a**; (ii) tautomerization and (iii) intramolecular conjugate addition to the vinylphosphonate function (Scheme 5). Reactions leading to products **6** can be



Scheme 5 *Reagents:* i, **1a**; ii, H^+

considered as examples of '2 + 4 MIMIRC' coupling,[16] similar to the first (in a sequence of two) annulation observed in the reaction between ethyl penta-2,4-dienoate and an allylic phosphonium ylide.[17]

In reaction of the salt **1a** with methyl methacrylate, the intermediate formed in the first step (conjugate addition *via* γ-carbon of the phosphonate) has a carbanionic centre developed at C-4 with respect to the β-carbon of the vinylphosphonic moiety, with no possibility of tautomerization to the 1,6-relationship, suitable for intramolecular ring closure. In this case the second step involved *intermolecular* conjugate addition to a second molecule of the methacrylate, yielding an intermediate capable of the final, 1,6-cyclization (Scheme 6).



Scheme 6 *Reagents:* i, **1a**; ii, methyl methacrylate; iii, H^+

Product **7** was identified by NMR (^1H, ^{13}C, ^{31}P) spectroscopy as a cyclic compound containing one molecule of phosphonate **1** and two molecules of methyl methacrylate incorporated into the 1,1,2,5,5-pentasubstituted cyclohexane derivative. The presence of only one phosphorus-31 signal, as well as only two for the methoxycarbonyl and two for the methyl groups in the NMR spectra of product **7** indicated that the reaction shown in Scheme 6 proceeded with the formation of a single stereoisomer. In terms of the sequence of the carbon–carbon bond-forming steps, synthesis of compound **7** represents extension of the reported[16] 2 + 2 + 2 construction of polyfunctionalized derivatives of cyclohexane.

Further reactions of phosphonate **1** and other alkenylphosphonates as synthons for the preparation of carbon skeletons are being currently investigated in our Laboratory.

Experimental

Solvents and commercially available substrates were purified by conventional methods immediately before use. All reactions were carried out in an atmosphere of dry nitrogen. TLC was carried out using precoated Kieselgel 60 F254 plastic plates. For column chromatography Merck Kieselgel 60 (0.063–0.200 mm) was used as stationary phase, and $CHCl_3$–acetone (4:1) as developer. Mass spectra were recorded on a Varian MAT-212 double-focusing direct-inlet spectrometer at an ionization potential of 70 eV. IR spectra were recorded as solutions in chloroform, with a Bruker IFS 113v FT-IR spectrometer. NMR spectra were recorded on a Bruker AC 300 MHz spectrometer for solutions in $CDCl_3$, and the chemical-shift values are given relative to $SiMe_4$ (^1H, ^{13}C) and trimethyl phosphate (^{31}P). Both ^1H-decoupled and ^1H-coupled ^{13}C NMR spectra were obtained for structural assignments. Heteronuclear proton–carbon correlation spectra, necessary for the assignment of signals, were obtained with a relaxation time of 1.7 s between scans, 64 values of *t*, and zero filling to 256 points in f_1 (^1H). *J*-Values are given in Hz. Diastereoisomeric nuclei (^1H, ^{13}C) are denoted by superscripts a and b. Elemental analyses (C/H) carried out at the Council for Scientific and Industrial Research (Pretoria) invariably gave, for compounds prepared in this work (and for other compounds containing *simultaneously* P–OC and P–C bonds), values lower (*ca.* 5%, rel.) than calculated. Since all compounds were homogeneous (TLC, ^{31}P NMR), and their MS showed molecular ions and expected fragmentation products, no elemental analysis data are given. Diethyl prop-2-enylphosphonate **1** was prepared as described in the literature,[18] and its NMR spectroscopic data were given before.[1]

Reactions of the Lithium Enolate **1a** *with Carbonyl Compounds. General Procedure.*—Butyllithium (1.6 mol dm^{-3} solution in hexane; 1.1 mol equiv.) was added to the solution of the phosphonate **1** (1.0 mol equiv.) in tetrahydrofuran (THF) at −78 °C, and the solution was stirred at this temperature for 1 h. Carbonyl substrate (1.0 mol equiv.) was then added dropwise to the mixture at −78 °C, the mixture was stirred at this temperature for 30 min, and was then allowed to warm up to room temperature. The mixture was stirred until the ^{31}P NMR spectrum of the sample of the reaction mixture showed the complete disappearance of substrate **1**. Saturated aq. ammonium chloride was added and the resulting solution was extracted with diethyl ether. The combined extracts were dried ($MgSO_4$), filtered, and evaporated under reduced pressure. The reaction products were purified and identified as indicated for individual compounds.

5-(*Diethoxyphosphoryl*)*hept*-6-*en*-2-*one** **2**. Reaction time 6 h; oil; purified by column chromatography (45%); ν_{max}/cm^{-1} 1712 (CO) and 1636 (C=C); *m/z* 248 (M^+, 19%), 205 (32), 191 (79), 178 (48), 149 (29), 122 (21) and 43 (100); δ_H 1.18 (3 H, t, J_{HH} 7.3, Me of POEt[a]), 1.19 (3 H, t, J_{HH} 7.1, Me of POEt[b]), 1.68

* *Systematic name:* Diethyl 1-(3-oxobutyl)prop-2-enylphosphonate.

(2 H, m, 4-H_2), 2.00 (3 H, s, COMe), 2.41 (3 H, m, 3-H_2 and 5-H), 3.97 (4 H, quint, J_{HH},J_{HP} 7.3, 2 × CH_2 of POEt), 5.08 (2 H, m, J_{tr} 16.2, J_c 10.0, J_{HP} 5.0, J_{gem} 1.8, J_{allyl} 1.3, 7-H_2) and 5.53 (1 H, m, J_{tr} 16.2, J_c 10.0, J_{vic} 6.2, J_{HP} 2.8, 6-H); δ_C 16.1 (d, J_{CP} 6.3, 2 × Me of POEt; J_{CH} 125), 22.0 (d, J_{CP} 5.4, C-4; J_{CH} 133), 29.7 (s, C-1; J_{CH} 127), 40.6 (d, J_{CP} 12.8, C-3; J_{CH} 126), 41.7 (d, J_{CP} 139, C-5; J_{CH} 148), 61.6 (d, J_{CP} 7.8, CH_2 of POEt[a]; J_{CH} 145), 61.9 (d, J_{CP} 7.1, CH_2 of POEt[b]; J_{CH} 152), 119.2 (d, J_{CP} 13.8, C-7; J_{CH} 157), 132.6 (d, J_{CP} 9.8, C-6; J_{CH} 158) and 207.4 (s, CO); δ_P 25.9.

Ethyl 4-(*diethoxyphosphoryl*)-3-*methylhex*-5-*enoate* **3**. Reaction time 40 min; oil; purified by column chromatography (70%); ν_{max}/cm^{-1} 1724 (CO) and 1635 (C=C); *m*/*z* 292 (M^+, 20%), 277 (2), 247 (45), 205 (100), 178 (35), 177 (85) and 149 (29); δ_H 1.00, 1.02 (3 H, 2 d, *J* 6.8, 7.0, 3-Me), 1.17, 1.18 (3 H, 2 t, *J* 7.2, Me of CO_2Et), 1.22, 1.25 (6 H, 2 t, *J* 7.2, 2 × Me of POEt), 2.12 (2 H, dd, J_{gem} 15.4, J_{vic} 4.6, 2-H_2), 2.51 (2 H, m, 3- and 4-H), 4.04 (6 H, m, 2 × CH_2 of POEt and CH_2 of CO_2Et), 5.13 (2 H, m, J_{tr} 17.1, J_c 9.1, J_{HP} 3.5, 6-H_2) and 5.67 (1 H, m, 5-H); δ_c 14.1 (s, Me of CO_2Et; J_{CH} 130), 16.3, 16.4 (2 d, J_{CP} 4.6, 2 × Me of POEt; J_{CH} 126), 18.7, 18.9 (2 s, 3-Me; J_{CH} 126), 29.6, 30.0 (2 d, J_{CP} 2.9, 4.0, C-3; J_{CH} 133), 38.3, 40.0 (2 d, J_{CP} 5.5, 14.8, C-2; J_{CH} 128), 46.9, 48.4 (2 d, J_{CP} 137.4, 138.6, C-4; J_{CH} 126), 60.0, 60.1 (2 s, CH_2 of CO_2Et; J_{CH} 147, 148), 61.7, 62.0 (2 d, J_{CP} 7.3, 2 × CH_2 of POEt; J_{CH} 150), 120.7, 121.2 (2 d, J_{CP} 14.2, 15.1, C-6; J_{CH} 156, 160), 129.7, 130.7 (2 d, J_{CP} 9.3, C-5; J_{CH} 154, 157) and 172.2, 172.6 (2 s, CO); δ_P 25.5 and 25.6.

4-[3′-(*Diethoxyphosphoryl*)*prop*-2′-*enyl*]-3,4-*dihydrocoumarin* **4**. Reaction time 3 h; oil; purified by bulb-to-bulb distillation (oven temp. 240 °C/0.3 mmHg) (83%); ν_{max}/cm^{-1} 1714 (CO); *m*/*z* 324 (M^+, 1%), 280 (3), 178 (87), 122 (33), 91 (29) and 44 (100); δ_H 1.27 (3 H, t, *J* 6.3, Me of POEt[a]), 1.30 (3 H, t, *J* 7.1, Me of POEt[b]), 2.50 (2 H, m, J_{vic} 7.7, 6.5, 1′-H_2), 2.78 (2 H, 2 dd, J_{gem} 16.2, J_{vic} 4.8, 3-H_2), 3.17 (1 H, m, J_{vic} 6.5, 4.8, 4-H), 4.06 (4 H, m, 2 × CH_2 of POEt), 5.67 (1 H, dd, J_{HP} 19.8, J_{tr} 17.1, 3′-H), 6.70 (1 H, m, J_{tr} 17.1, J_{vic} 7.7, 2′-H) and 7.16 (4 H, m, ArH); δ_c 16.3 (d, J_{CP} 7.9, 2 × Me of POEt; J_{CH} 126), 34.3 (d, J_{CP} 2.6, C-1′; J_{CH} 135), 39.0 (s, C-3; J_{CH} 134), 39.3 (s, C-4; J_{CH} 137), 61.8 (d, J_{CP} 6.6, 2 × CH_2 of POEt; J_{CH} 147), 117.0 (s, C-4a), 117.3 (s, C-8; J_{CH} 156), 121.4 (d, J_{CP} 187, C-3′; J_{CH} 156), 124.6 (s, C-6; J_{CH} 161), 127.6 (s, C-5; J_{CH} 162), 128.8 (s, C-7; J_{CH} 164), 148.1 (d, J_{CP} 5.5, C-2′; J_{CH} 156); δ_P 14.5.

7-(*Diethoxyphosphoryl*)*hepta*-3,5-*dien*-2-*one** **5**. Reaction time 1 h; oil; purified by column chromatography (62%); ν_{max}/cm^{-1} 1667 (CO), 1632 and 1595 (C=C); *m*/*z* 246 (M^+, 12%), 108 (100), 81 (17) and 43 (35); δ_H 1.25 (6 H, t, *J* 7.1, 2 × Me of POEt), 2.20 (3 H, s, 1-H_3), 2.67 (2 H, dd, J_{HP} 23.2, J_{vic} 7.6, 7-H_2), 4.05 (4 H, quint, J_{HP}, J_{vic} 7.1, 2 × CH_2 of POEt), 6.04 (2 H, m, J_{HP}, J_{tr} 5.1, 7.4; J_{tr} 15.3, 6- and 3-H), 6.23 (1 H, m, J_{HP} 4.8, J_{vic} 10.8, J_{tr} 15.3, 5-H) and 7.03 (1 H, dd, J_{vic} 10.8, J_{tr} 15.3, 4-H); δ_C 16.3 (d, J_{CP} 6.8, 2 × Me of POEt; J_{CH} 124), 27.1 (s, C-1; J_{CH} 128), 31.3 (d, J_{CP} 140, C-7; J_{CH} 137), 62.1 (d, J_{CP} 7.1, 2 × CH_2 of POEt; J_{CH} 148), 130.3 (d, J_{CP} 4.2, C-5; J_{CH} 149), 132.3 (d, J_{CP} 12.5, C-5; J_{CH} 173), 133.0 (d, J_{CP} 13.4, C-6; J_{CH} 163), 142.1 (d, J_{CP} 4.5, C-4; J_{CH} 153) and 198.3 (s, CO); δ_P 22.9.

3-(*Diethoxyphosphorylmethyl*)-5-*phenylcyclohexanone*† **6a**. Reaction time 7 h; oil; purified by column chromatography (66%); ν_{max}/cm^{-1} 1710 (CO); *m*/*z* 324 (M^+, 55%), 295 (28), 267 (18), 186 (50), 152 (100), 139 (50), 123 (21), 97 (39), 91 (27) and 43 (22); δ_H 1.22 (3 H, t, *J* 7.2, Me of POEt[a]), 1.23 (3 H, t, *J* 7.2, Me of POEt[b]), 1.75 (2 H, dd, J_{HP} 19.0, J_{vic} 6.8, PCH_2), 2.08 (1 H, m, J_{gem} 14.2, J_{vic} 3.9, 3.4, 4-H_{eq}), 2.31 (1 H, dd, J_{gem} 13.8, J_{vic} 5.4, 2-H_{ax}), 2.59 (4 H, m, J_{gem} 13.8, J_{vic} 6.2, 6.0, 5.6, 3.4 and 2.7, 2-H_{eq}, 3-H_{ax}, and 6-H_2), 3.31 (1 H, m, J_{vic} 8.6, 5.6, 3.9 and 2.7, 5-H_{ax}), 4.00 (4 H, quint, J_{HP} = J_{vic} = 7.2, 2 × CH_2 of POEt) and 7.22 (5 H, m, Ph); δ_C 16.3 (d, J_{CP} 6.9, 2 × Me of POEt; J_{CH} 130), 29.6 (d, J_{CP} 4.2, C-3; J_{CH} 139), 30.3 (d, J_{CP} 140.8, PCH_2; J_{CH} 144), 38.0 (d, J_{CP} 8.8, C-4; J_{CH} 125), 39.2 (s, C-5; J_{CH} 129), 46.9 (s, C-6; J_{CH} 126), 47.5 (d, J_{CP} 11.8, C-2; J_{CH} 125), 61.4 (d, J_{CP} 8.2, CH_2 of POEt[a]; J_{CH} 145), 61.5 (d, J_{CP} 8.3, CH_2 of POEt[b]; J_{CH} 145), 126.5 (s, C-4′ of Ph; J_{CH} 154), 126.8 (s, C-2′, -6′ of Ph; J_{CH} 154), 128.6 (s, C-3′, -5′ of Ph; J_{CH} 154), 143.5 (s, C-1′ of Ph) and 21.0 (s, C-1); δ_P 27.1.

5-(*Diethoxyphosphorylmethyl*-3,3-*dimethylcyclohexanone*‡ **6b**. Reaction time 7 h; oil; purified by column chromatography (75%); ν_{max}/cm^{-1} 1708 (CO); *m*/*z* 276 (M^+, 14%), 261 (6), 247 (4), 139 (97), 138 (100), 111 (25), 108 (14) and 97 (26); δ_H 0.88 (3 H, s, Me_{ax}), 1.05 (3 H, s, Me_{eq}), 1.28 (6 H, t, *J* 7.0, 2 × Me or POEt), 1.32 (1 H, m, J_{gem} 13.3, J_{vic} 12.4, 4-H_{ax}), 1.72 (2 H, m, J_{HP} 18.1, J_{vic} 6.6, 5.4, PCH_2), 1.81 (1 H, m, J_{gem} 13.3, J_{vic} 5.5, 4-H_{eq}), 1.95 (1 H, m, J_{gem} 11.6, J_{vic} 11.0, 6-H_{ax}), 2.02 [1 H, m, J_{gem} 13.5, J_w (6-H_{ax}), 2.1, 2-H_{ax}], 2.10 (1 H, d, J_{gem} 13.5, 2-H_{eq}), 2.28 (1 H, m, J_{vic} 12.4, 11.0, 6.6, 5.8, 5.5 and 5.4, 5-H_{ax}), 2.50 (1 H, m, J_{gem} 11.6, J_{vic} 5.8, 6-H_{eq}) and 4.05 (4 H, m, 2 × CH_2 of POEt); δ_C 16.5 (d, J_{CP} 5.8, 2 × Me of POEt; J_{CH} 127), 25.6 (s, Me_{ax}; J_{CH} 123), 29.7 (d, J_{CP} 4.6, C-5; J_{CH} 125), 32.0 (s, Me_{eq}; J_{CH} 126), 33.0 (d, J_{CP} 140.1, PCH_2; J_{CH} 141), 34.9 (d, J_{CP} 2.7, C-3), 46.0 (d, J_{CP} 10.9, C-4; J_{CH} 126), 47.9 (d, J_{CP} 9.8, C-6; J_{CH} 126), 54.1 (s, C-2; J_{CH} 126), 61.4 (d, J_{CP} 3.9, CH_2 of POEt[a]; J_{CH} 147), 61.5 (d, J_{CP} 3.9, CH_2 of POEt[b]; J_{CH} 147) and 210.2 (s, C-1); δ_P 27.1.

syn-6-(*Diethoxyphosphorylmethyl*)*bicyclo*[2.2.2]*octan*-2-*one*§ **6c**. Reaction time 8 h; oil; purified by column chromatography (60%); ν_{max}/cm^{-1} 1717 (CO); *m*/*z* 274 (M^+, 8%), 261 (9), 178 (15), 152 (100) and 97 (6); δ_H 1.12 (3 H, t, *J* 6.9, Me or POEt[a]), 1.13 (3 H, t, *J* 7.1, Me of POEt[b]), 1.15 (1 H, m, 5-H_{syn}), 1.30–1.80 (6 H, m, PCH_2 and 7- and 8-H_2), 1.90–2.13 (5 H, m, 1-H, 3-H_2, 4-H and 5-H_{anti}), 2.22 (1 H, m, 6-H) and 3.90 (4 H, m, 2 × CH_2 of POEt); δ_C 16.4 (d, J_{CP} 7.0, 2 × Me of POEt; J_{CH} 122), 23.0 (s, C-7; J_{CH} 135), 23.2 (s, C-8; J_{CH} 135), 28.0 (s, C-4; J_{CH} 137), 31.3 (d, J_{CP} 4.2, C-6; J_{CH} 125), 33.3 (d, J_{CP} 135.0, PCH_2; J_{CH} 127), 34.2 (d, J_{CP} 12.0, C-5), 44.8 (s, C-3; J_{CH} 127), 48.8 (d, J_{CP} 7.6, C-1; J_{CH} 135), 61.5 (d, J_{HP} 7.6, 2 × CH_2 of POEt; J_{CH} 148) and 208.8 (s, CO); δ_P 27.4.

syn-6-(*Dimethoxyphosphorylmethyl*)-4-*methylbicyclo*[2.2.2]*octan*-2-*one*¶ **6d**. Reaction time 8 h; oil; purified by column chromatography (69%); ν_{max}/cm^{-1} 1716 (CO); *m*/*z* 288 (M^+, 35%), 260 (86), 245 (16), 231 (29), 217 (6), 180 (100), 179 (95), 152 (63) and 138 (51); δ_H 0.76 (3 H, s, 4-Me), 1.00 [1 H, ddd, J_{gem} 13.7, J_{vic} 5.9, J_w (8-H_{syn}), 2.8, 5-H_{syn}), 1.11 (3 H, t, *J* 7.0, Me of POEt[a]), 1.12 (3 H, t, *J* 7.1, Me of POEt[b]), 1.28 (2 H, m, 8-H_2), 1.34 (1 H, ddd, J_{HP} 18.5, J_{gem} 15.2, J_{vic} 9.3, PCH[a]), 1.53 (1 H, ddd, J_{HP} 19.0, J_{gem} 15.2, J_{vic} 5.3, PCH[b]), 1.65 (2 H, m, 7-H_2), 1.73 (1 H, d, J_{gem} 18.8, 3-H_{syn}), 1.74 [1 H, m, J_{gem} 13.7, J_{vic} 12.1, J_w (3-H_{anti}), 3.2 5-H_{anti}], 1.90 [1 H, dd, J_{gem} 18.8, J_w (5-H_{anti}), 3.2 3-H_{anti}], 2.00 (1 H, m, J_{vic} 3.4, 2.6, 1-H), 2.20 (1 H, m, 6-H) and 3.88 (4 H, m, J_{HP} 7.2, J_{vic} 7.0, 2 × CH_2 of POEt); δ_C 16.3 (d, J_{CP} 6.2, 2 × Me of POEt; J_{CH} 129), 23.1 (s, C-7; J_{CH} 132), 26.7 (s, 4-Me; J_{CH} 121), 30.2 (s, C-8; J_{CH} 128), 31.1 (d, J_{CP} 4.2, C-6; J_{CH} 133), 32.6 (s, C-4), 32.7 (d, J_{CP} 140, PCH_2; J_{CH} 129), 40.8 (d, J_{CP} 7.0, C-5; J_{CH} 133), 48.3 (d, J_{CP} 13.9, C-1; J_{CH} 143), 50.4 (s, C-3; J_{CH} 131), 61.1 (d, J_{CP} 6.8, 2 × CH_2 of POEt; J_{CH} 149) and 215.7 (s, CO); δ_P 27.4.

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* *Systematic name:* Diethyl 6-oxohepta-2,4-dienylphosphonate.
† *Systematic name:* Diethyl (3-oxo-5-phenylcyclohexyl)methylphosphonate.
‡ *Systematic name:* Diethyl (3,3-dimethyl-5-oxocyclohexyl)methylphosphonate.
§ *Systematic name:* Diethyl (6-oxobicyclo[2.2.2]octan-2-yl)methylphosphonate.
¶ *Systematic name:* Diethyl (4-methyl-6-oxobicyclo[2.2.2]octan-2-yl)-methylphosphonate.

2-(*Diethoxyphosphorylmethyl*)-1,5-bis(*methoxycarbonyl*)-1,5 *dimethylcyclohexane** **7**. Reaction time 1 h; oil; purified by column chromatography (eluent ethyl acetate) (60%); ν_{max}/cm^{-1} 1723 (CO); *m*/*z* 378 (M^+, 7%), 304 (6), 291 (26), 245 (7), 191 (100), 81 (17) and 41 (99); δ_H 0.89 (3 H, s, 1-Me), 1.09 (3 H, s, 5-Me), 1.14 (1 H, m, 4-H_{ax}), 1.25 (3 H, t, *J* 6.8, Me of POEt[a]), 1.28 (3 H, t, *J* 7.0, Me of POEt[b]), 1.37 (1 H, m, 3-H_{ax}), 1.54 (2 H, ddd, J_{HP} 21.5, J_{gem} 15.3, J_{vic} 2.0, PCH_2), 1.64 (1 H, d, J_{gem} 13.9, 6-H_{ax}), 1.99 (1 H, m, J_{gem} 13.9, J_{vic} 7.0, 3.3, 3-H_{eq}), 2.23 (3 H, m, 2-H), 4-H_{eq} and 6-H_{eq}), 3.60 (3 H, s, 5-CO_2Me), 3.62 (3 H, s, 1-CO_2Me) and 4.02 (4 H, m, *J* 6.8, 7.0, 2 × CH_2 of POEt); δ_C 14.4 (s, 1-Me; J_{CH} 126), 16.3 (d, J_{CP} 7.8, 2 × Me of POEt; J_{CH} 128), 25.1 (s, C-3; J_{CH} 130), 28.0 (d, J_{CP} 140.1, PCH_2; J_{CH} 143), 29.4 (s, 5-Me; J_{CH} 129), 34.4 (s, C-4; J_{CH} 130), 36.6 (d, J_{CP} 3.8, C-2; J_{CH} 138), 40.5 (s, C-5), 44.8 (s, C-6; J_{CH} 130), 47.5 (d, J_{CP} 16.7, C-1), 51.5 (s, 5-CO_2*Me*; J_{CH} 147), 52.0 (s, 1-CO_2*Me*; J_{CH} 147), 61.3 (d, J_{CP} 7.0, CH_2 of POEt[a]; J_{CH} 148), 61.5 (d, J_{CP} 6.9, CH_2 of POEt[b]; J_{CH} 148) and 177.5 (s, 2 × CO); δ_P 29.2.

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