New syntheses of 1-chloroalkylphosphinates

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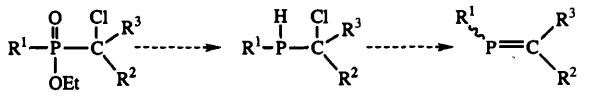
Different approaches to the synthesis of 1-chloroalkylphosphinates are described. Initially, we tried to extend a reaction described by Kabachnik for the preparation of chloromethylphosphinic acid chlorides [R^1(Cl)P(O)CH_2Cl] to C-substituted derivatives. We also considered the possibility of synthesizing the title compounds by routes already described for the formation of diethyl 1-chloroalkylphosphonates. Although these methods have allowed us to obtain several of the desired phosphinates, they suffer from limitations that restrict their synthetic applications. Finally, we have developed a more general approach that allows the formation of a wide range of phosphinates. It involves a selective P–C bond formation by reaction of MeMgCl and PhMgCl with phosphonochloridates, which are prepared by P-chlorination of 1-chloroalkylphosphonates.

Introduction

From organic and polymer syntheses[1] to biology and biochemistry,[2] phosphonate and phosphinate derivatives have such a wide range of properties and applications that they have stimulated an enormous amount of study for several decades. However, development of novel synthetic routes to these classes of compounds and introduction of phosphorus-containing groups into molecules with the aim of modifying their chemical, physical or biological properties are still the targets of much research. The synthetic importance of 1-chloroalkylphosphonates has been known for many years. They are, for example, implicated in the preparation of unsaturated α-chloro-α,β-ethylenic carboxylic acids,[3] 1,2-epoxyalkylphosphonates[4] or alkylidene-mono- or -di-phosphonates.[5] As part of our ongoing interest in the chemistry of low valent phosphorus compounds, we have recently shown that they are key intermediates for the synthesis of non-stabilized phospha-alkenes of the type [RCH=PH][6] in a two-step sequence that involves a reduction of the phosphonates into the corresponding primary 1-chloroalkylphosphines followed by HCl elimination.[7] We are now interested in preparing the P-substituted derivatives and have therefore focused our attention on the preparation of 1-chloroalkylphosphinates. Access to this class of compounds should allow us to develop a general approach to non-stabilized phospha-alkenes that offers the possibility of controlling both the P and C substitutents (Scheme 1).



Scheme 1

Although several routes to 1-chloroalkylphosphonates are described in the literature,[7–14] 1-chloroalkylphosphinates **3** have surprisingly received little attention. In this paper we report our investigations into the preparation of this class of compounds. At first our synthetic strategy involved the use of R^1PX_2 (X = Cl or OR) as a starting material, and three different approaches were considered. They are applications or extensions of previously reported procedures, and involve: (i) extension of Kabachnik's approach to the synthesis of [R^1(EtO)P(O)CH_2Cl][15] to the formation of C-substituted derivatives (route A); (ii) C-chlorination of 1-hydroxyphosphinates (route B); and (iii) C-alkylation of trichloromethylphosphinates (route C), the last two being efficient for the synthesis of 1-chloroalkylphosphonates.[7,9] However, these methods suffer from limitations (low yields and lack of generality). We have developed a more general approach, which involves a selective P-substitution of phosphonochloridates. This new sequence allows the formation of a broad range of 1-chlorophosphinates and seems to be generally applicable.

Results and discussion

Kabachnick's procedure (route A)

Initially the most attractive and straightforward method to 1-chloroalkylphosphinates **3** would have been the esterification of alkyl(chloroalkyl)phosphinic chlorides [R^1(Cl)P(O)CR^2(H)Cl] **2**. Kabachnik and Shepeleva have reported the synthesis of **2a** (R^1 = Ph; R^2 = H) and **2b** (R^1 = Me; R^2 = H) by condensation of paraformaldehyde and dichlorophosphines **1** under rather drastic conditions.[15] Subsequent ethanolysis leads to the corresponding phosphinates **3a** (R^1 = Ph, R^2 = H) and **3b** (R^1 = Me, R^2 = H) (Scheme 2, route A). This sequence gives moderate overall yields (*ca.* 25–30%, Table 1) but has the advantage of simplicity. However significant difficulties were encountered while attempting to condense dichlorophosphines with higher aldehyde homologues. Consequently this route was not further studied.

C-Chlorination of α-hydroxyphosphinates (route B)

Another possible route for the preparation of the title compounds consisted of extending the methodology used for the synthesis of 1-chloroalkylphosphonates,[7] which involves the C-chlorination of α-hydroxyphosphonates using a thionyl chloride–pyridine mixture in refluxing toluene. Therefore we assumed that the 1-chloroalkylphosphinates **3** could be prepared in a similar manner from the hydroxyphosphinates **5** (Scheme 2, route B).

To the best of our knowledge the synthesis of 1-hydroxyphosphinates has been little studied. Foucaud and Texier have reported the synthesis of 1-hydroxyphosphonates by condensation of an aldehyde with diethylphosphite [$HP(O)(OEt)_2$] in a dry medium (alumina).[16] By using this

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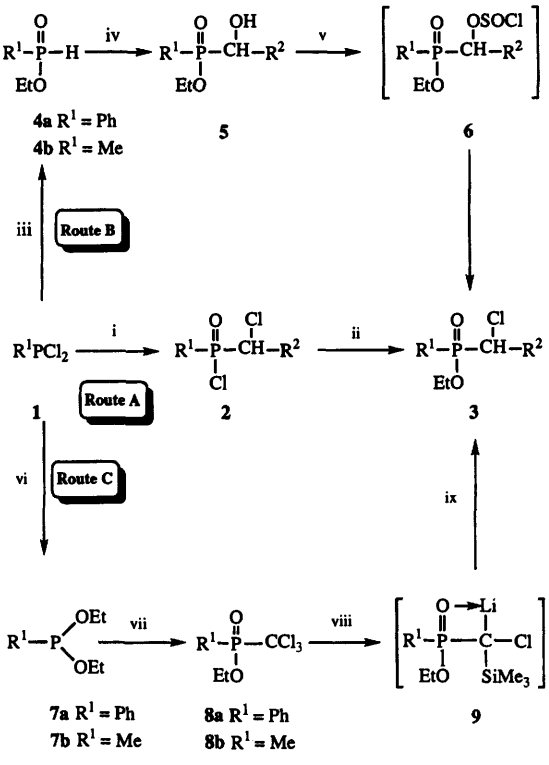
Table 1 Methods for the synthesis of the ethyl 1-chloroalkylphosphinates [$R^1(OEt)P(O)(CClR^2H)$] **3** and ^{31}P NMR chemical shifts

Compound	R^1	R^2	Method of preparation (yield %)[a]	δ_P[b]
3a	Ph	H	A (25), C (61), D (63)	34.90
3b	Me	H	A (30), D (65)	47.58
3c	Ph	Me	B (38), C (61), D (60)	38.33, 37.31
3d	Ph	Et	B (35), C (61), D (56)	36.54, 37.57
3e	Ph	CH_2=CH	B (6)	34.46, 33.90
3f	Ph	MeCH=CH	C (61)	32.92, 34.04
3g	Ph	Ph	B (65), D (68)	33.50, 34.12
3h	Me	Me	D (66)	50.02, 51.51
3i	Me	Et	D (58)	48.60, 49.40

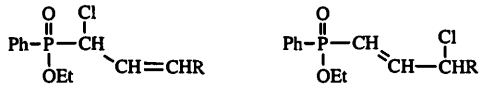
[a] Overall yields based on R^1PCl_2 (methods A, B and C) (see Scheme 2) and on diethyl 1-chloroalkylphosphonates (method D) (see Scheme 3). [b] ^{31}P NMR chemical shifts (one or two diastereoisomers were obtained).



Scheme 2 i, R^2CHO, heat; ii, EtOH, base; iii, 2 EtOH; iv, R^2CHO, alumina-KF; v, $SOCl_2$, pyridine, toluene, heat; vi, 2 EtOH, 2 Et_3N; vii, CCl_4, heat; viii, Me_3SiCl, BuLi (2 equiv. *x*); ix, R^2X, H_2O, LiOH

method we have been able to prepare the hydroxyphosphinates **5** (**a**: R^1 = Ph, R^2 = Me; **b**: R^1 = Ph, R^2 = Et; **c**: R^1 = R^2 = Ph; **d**: R^1 = Ph, R^2 = vinyl; **e**: R^1 = Ph, R^2 = allyl; **f**: R^1 = R^2 = Me; **g**: R^1 = Ph, R^2 = Et), from the corresponding alkyl- or aryl-phosphonite [$R^1(EtO)P(O)H$] **4a** (R^1 = Ph) and **4b** (R^1 = Me)[17,18] (Scheme 2, route B). A complete transformation was achieved in both cases on activated alumina (see Table 2). The hydroxyphosphinates **5** were extracted with CH_2Cl_2 and obtained as mixtures of two diastereoisomers in good yields (*ca.* 80%). The ^{31}P NMR chemical shifts are given in Table 2. The ratio between the two diastereoisomers was estimated from the ^{31}P NMR spectra. It is notable that the ^1H and ^{13}C NMR spectra did not always show the expected two sets of signals for all the groups of compounds **5**. This is probably due to the proximity of the chemical shifts in these cases.

The chlorination of the hydroxyphosphinates **5** using the $SOCl_2$–pyridine procedure described above was difficult to carry out selectively. Thus, when R^1 = Me the desired 1-chloroalkylphosphinates could not be obtained by this method. The reaction was accompanied by the formation of numerous by-products resulting from P–C and P–O bond cleavage. To overcome these problems we pursued milder reaction conditions and tried other chlorinating agents such as *N*-chlorosuccinimide (NCS), $COCl_2$ and CCl_4–PPh_3. However, no improvement was obtained. When R^1 = Ph the formation of by-products could not be avoided but could be limited, since the reaction could be carried out at 65 °C (below that temperature the SO_2 extrusion from the chlorosulfite intermediate **6** does not take place). In these conditions the phosphinates **3c** (R^1 = Ph, R^2 = Me), **3d** (R^1 = Ph, R^2 = Et) and **3g** (R^1 = Ph, R^2 = Ph) were obtained as the main products. The first two were purified by fractional distillation, but the overall yields were moderate at best (*ca.* 35%, Table 1), whereas the latter was directly obtained in an analytically pure form. The C-chlorination of **5d** and **5e** was accompanied by an allylic rearrangement that led almost exclusively to the formation of the 3-chloroalkenyl derivatives **10a** and **10b** respectively (Scheme 3). For compound **10a**, the



Scheme 3

splitting of the vinylic proton CH=C*H*P (δ 6.18, dd, J 20 and 17 Hz) corresponds to the $^3J_{HHtrans}$ and $^2J_{PH}$ coupling constants. These values are, however, too close together to be attributed.

In conclusion, the selectivity of the C-chlorination of 1-hydroxyphosphinates was found to be strongly dependent upon the substitution of both the phosphorus and the carbon atoms. Thus *P*-phenyl derivatives are obtained with moderate overall yields (*ca.* 35%, Table 1) whereas γ-chlorovinyl phosphinates, which represent interesting precursors for the preparation of 1-phosphabutadienes, are isolated in satisfactory yields. However, the formation of the *P*-methyl phosphinates was strongly limited due to uncontrolled side reactions.

(iii) C-alkylation of trichloromethylphosphinates (route C)

We have already developed an efficient synthesis of 1-chloroalkylphosphonates from the trichloromethylphosphonate [$Cl_3CP(O)(OEt)_2$], the key reaction being the alkylation of the intermediate [$(Me_3Si)CCl(Li)P(O)(OEt)_2$] followed by desilylation.[10] We have now tested the applicability of this sequence to the preparation of the ethoxy (chloroalkyl)phosphinates **3** (Scheme 2, route C). The diethyl phosphonite precursors **7a** (R^1 = Ph) and **7b** (R^1 = Me) were prepared by ethanolysis of the corresponding dichlorophosphines **1** in the presence of a Lewis base. A Michaelis–Arbuzov type reaction[18] between **7a** and CCl_4 in excess afforded the trichloromethylphosphinate **8a** (R^1 = Ph) in a good yield (> 85%). However the formation of **8b** (R^1 = Me) was always accompanied by that of Me-$P(O)(OEt)_2$ (30%, δ_P 38.4). Treatment of **8a** with 2 equiv.

Table 2 Reaction conditions for the formation of the 1-hydroxyphosphinates 5, yields and ^{31}P NMR chemical shifts

Compound	R^1	R^2	KF[a] (%)	R^2CHO[b]	δ_P(ppm) (a:b)[c]	Yield (%)
5a	Ph	Me	1	3.5	42.2, 42.7 (3:2)	86
5b	Ph	Et	1	3.5	41.6, 41.8 (3:2)	85
5c	Ph	Ph	1	1.1	39.5, 39.9 (1:1)	84
5d	Ph	CH_2=CH	1	3	35.5, 35.9 (1:1)	79
5e	Ph	MeCH=CH	1	2.5	36.3, 36.5 (1:1)	77
5f	Me	Me	5	2	54.1, 54.8 (1:1)	85
5g	Me	Et	5	2	51.7, 52.5 (3:2)	81

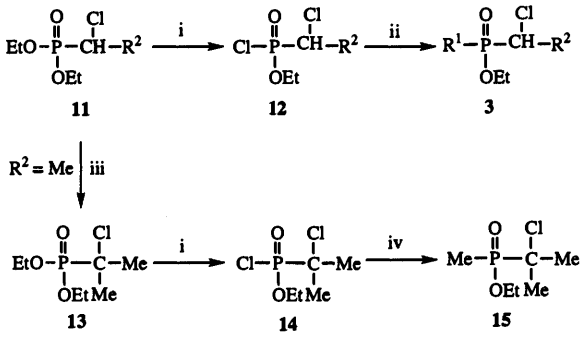
[a] Mass KF/mass alumina. [b] Equivalents per mole of phosphonite **3**. [c] ^{31}P NMR chemical shifts, two diastereoisomers observed in an a:b ratio.

of butyllithium and 1 equiv. of trimethylchlorosilane at −80 °C led to the lithiated phosphinate **9**. This yellow coloured intermediate is stable up to 0 °C as monitored by ^{31}P NMR. It is notable that only one signal was observed (δ_P 48.7), whereas two diastereoisomers were expected. This demonstrates that this derivative rapidly equilibrates in a very short lifetime. Addition of R^2X (R^2 = Me, Et, Allyl; X = I, Br) at −30 °C and subsequent hydrolysis by LiOH–H_2O yielded the desired α-chlorophosphinates **3a**, **3d** and **3f** respectively. Similar treatment of *P*-methyl derivative **8b** led to the formation of many by-products, which presumably result from competitive nucleophilic attack by the chlorine atoms of CCl_3 and hydrogen atoms of the methyl group. Attempts at optimizing this reaction were not successful. This approach is efficient for the preparation of the *P*-phenyl compounds **3** (overall yields of *ca.* 60%).

In addition to the synthetic problems encountered, another drawback to the three approaches described above lies in the fact that very few of the dichlorophosphine starting materials **1** are available and that their preparation is both tedious and restricted to certain substituents.[11,19] This led us to consider alternative ways to prepare the title compounds from more accessible precursors.

Reaction of phosphonochloridates with MeMgCl and PhMgCl (route D)

We have recently described the synthesis of phosphonochloridates by chlorination of phosphonates with $POCl_3$.[20] This reaction proceeds selectively under mild conditions and allows the formation on a large scale of a wide range of phosphonochloridates. Thus treatment of easily prepared 1-chlorophosphonates [$(EtO)_2(O)PCH(Cl)R^2$] **11** (**a**: R^2 = H; **b**: R^2 = Me; **c**: R^2 = Et; **d**: R^2 = Ph) with 1.1 equiv. of $POCl_3$ in the absence of solvent afforded the corresponding phosphonochloridates [$(EtO)Cl(O)PCH(Cl)R^2$] **12** (**a**: R^2 = H; **b**: R^2 = Me; **c**: R^2 = Et; **d**: R^2 = Ph) in high yields (*ca.* 80%) (Scheme 4). Therefore it appeared that the latter would be valuable precursors to the 1-chloroalkylphosphinates, provided that they could be substituted selectively at the phosphorus centre. We found that treatment of **11** at −70 °C with 1 equiv. of R^1MgCl (R^1 = Ph or Me) fulfilled this requirement, thus leading to the expected saturated phosphinates **3**, with overall yields of *ca.* 60%. This approach can also be extended to the formation of C-disubstituted derivatives, such as [(EtO)Me(O)PC(Cl)Me_2] **15** (Scheme 4), thus offering the possibility of controlling both the P and the C substitution.



Scheme 4 i, $POCl_3$; ii, R^1MgCl, −70 °C to room temp.; iii, BuLi, −80 °C, MeI; iv, MeMgCl, −70 °C to room temp.

Conclusion

Ethyl 1-chloroalkylphosphinates **3** have been prepared by different synthetic approaches as reported in Table 1. Routes A, B and C (Scheme 2) suffer from a lack of generality and from the difficulty of acquiring or preparing the dichlorophosphine precursors. The reaction described by Kabachnik (route A) is limited to the synthesis of C-unsubstituted derivatives with overall yields of *ca.* 25–30%. The C-chlorination of α-hydroxyphosphinates (route B) and C-alkylation of trichloromethylphosphinates (route C) are useful methods for the synthesis of the *P*-phenyl derivatives, yet with moderate overall yields (*ca.* 35% and 60% respectively; yields are based on R^1PCl_2). However these methods do not apply to the preparation of the *P*-methyl derivatives. We have developed another approach (route D; Scheme 4) that involves reaction of phosphonochloridates with Grignard reagents. The 1-chloroalkylphosphonate starting materials are easier to handle and more accessible than the dichlorophosphines. This method allows the formation of a wide range of phosphinates, including the P-methylated products.

Experimental

All the reactions were carried out under an atmosphere of dried nitrogen in oven-dried glassware. Diethyl ether, tetrahydrofuran and toluene were distilled from sodium–benzophenone just before use. Dichloromethane was distilled from phosphorus pentoxide and stored over molecular sieves (4 Å). Pyridine was distilled from and stored over potassium hydroxide. Thionyl chloride was distilled from magnesium just before use. IR spectra were obtained on a Perkin-Elmer Model 157G using KBr windows. ^1H, ^{13}C and ^{31}P NMR spectra were recorded on a Bruker WP 80 DS (^1H, 80 MHz; ^{13}C, 20.115 MHz; ^{31}P, 32.38 MHz) at the Centre Régional de Mesures Physiques de l'Ouest (CRMPO) or on a Bruker AC 300 P (^1H, 300 MHz; ^{13}C, 75.47 MHz; ^{31}P, 121.496 MHz). Chemical shifts (δ) are given in ppm relative to internal $SiMe_4$ for ^1H and ^{13}C NMR spectra and H_3PO_4 for ^{31}P NMR spectra. Unless stated otherwise, commercial (Aldrich) $CDCl_3$ was used as the deuteriated solvent. Coupling constants (J) are given in Hz and the following abreviations are used for the multiplicity: s = singlet, d = doublet, t = triplet, q = quartet, quin = quintet, m = multiplet. Chemical shifts downfield from the standard are defined as positive. High resolution mass spectra were recorded on a Varian MAT 311 spectrometer (CRMPO). Standard neutral alumina (Merck, type 60), acetaldehyde, propionaldehyde, acrylaldehyde, crotonaldehyde (Aldrich or Janssen) and dichlorophosphines **1** (Strem) were used as received. Compounds **4**,[17,18] **7**,[21] **11**[7] and **12a–b**[20] were prepared as already reported. All the derivatives which have been used as

intermediates for the different syntheses of the title compounds **3** have been fully characterized.

Synthesis of the 1-chloroalkylphosphinates 3

These compounds were prepared by the use of one or several of the three methods described below (see Table 2 for overall yields).

Chlorination of the 1-hydroxyphosphinates 5 (Method B). A 50 ml toluene solution of thionyl chloride (6.1 ml, 0.075 mol) was added dropwise to a mixture of **5** (0.05 mol) and 7.3 ml of pyridine (0.09 mol) in 200 ml of toluene at 0 °C (ice bath). The mixture was then heated to 65 °C for a period of 5–12 h, depending on the phosphinate starting material. After it had cooled to room temp., the reaction mixture was washed with HCl (0.5 M solution; 2 × 20 ml), water (20 ml), 10% aqueous sodium carbonate (2 × 20 ml), water (20 ml) and saturated aqueous NaCl (20 ml). The organic fraction was then dried over $MgSO_4$ and the solvent removed *in vacuo*. The products were purified by fractional distillation under reduced pressure or by use of a Kugelrhor.

Alkylation of the ethyl trichlomethylphosphinates 8 (Method C). In a 500 ml three-necked round bottom flask, equipped with a mechanical stirrer, a dropping funnel, a gas inlet tube and a thermometer, were placed BuLi (0.04 mol) and 150 ml of freshly distilled THF. The solution was cooled to −85 °C (internal temperature) and stirred vigorously while a THF solution (100 ml) of **8** (0.02 mol) and Me_4SiCl (0.02 mol, 2.54 ml) was added dropwise. The reaction mixture was allowed to warm to −30 °C and an alkyl halide (0.02 mol) was added. The mixture was then stirred at room temperature for 1 h. One of two different work-ups was then used.

(*a*) A NaOH (2 M) solution was added until the mixture reached basic pH. The resulting biphasic mixture was shaken overnight. The THF fraction was then collected and the aqueous layer washed with CH_2Cl_2 (2 × 50 ml). The organic fractions were combined and dried over Na_2SO_4. After evaporation of the solvents the residue was distilled.

(*b*) The mixture was acidified (HCl, 6 M). After decantation and extraction with CH_2Cl_2 (2 × 50 ml), the organic fraction was dried over Na_2SO_4 and the solvents eliminated under reduced pressure. The residue $[R^1P(O)(OEt)CClR^2(SiMe_3)]$ was dissolved in EtOH (100 ml) and a piece of lithium or sodium metal was added. The solution was stirred for 1 h at room temperature and then acidified (HCl, 12 M). The mixture was concentrated under reduced pressure. Water (50 ml) was then added and the desired phosphinate was extracted with Et_2O. The solution was washed with water, dried and concentrated *in vacuo*. The phosphinates were purified by fractional distillation.

Alkylation of the ethyl 1-chloroalkylphosphonochloridates 12 (Method D). In a 500 ml three-necked round bottom flask, equipped with a mechanical stirrer, a dropping funnel, a gas inlet tube and a thermometer, were placed **12** (0.05 mol) in 150 ml of a 1:1 mixture of Et_2O–THF. The mixture was cooled to −70 °C (internal temperature) and a Grignard chloride (0.05 mol) in a THF solution was then added dropwise, while vigorous stirring was maintained. The reaction mixture was allowed to warm to room temperature, and was then poured into a flask containing 50 ml of cold (0 °C) saturated aqueous NH_4Cl. The aqueous layer was then washed with Et_2O (3 × 50 ml). The organic layers were combined and dried over $MgSO_4$. After evaporation of the solvent the desired phosphinates were obtained with a purity higher than 95%. They were purified by fractional distillation.

Ethyl phenyl(chloromethyl)phosphinate 3a. This compound was prepared by method C (yield 85%) or method D (yield 77%), bp 119 °C/0.4 mmHg; δ_H 1.38 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 3.65 (2 H, d, $^2J_{PH}$ 8, PCH_2Cl), 4.15 (2 H, quin, $^3J_{HH} = {}^3J_{PH}$ = 7, MeCH_2O), 7.55–7.85 (5 H, m, Ph); δ_C 16.49 ($^3J_{CP}$ 6, *Me*CH_2O), 36.67 ($^1J_{CP}$ 105, PCH_2Cl), 61.96 ($^2J_{CP}$ 6, OCH_2Me), 127.94 (Ph, C_{ipso}), 128.8 ($^3J_{CP}$ 13, Ph, C_{meta}), 132.31 ($^2J_{CP}$ 10, Ph, C_{ortho}), 133 ($^4J_{CP}$ 3, Ph, C_{para}) (Found: H, 5.39; P, 13.95. Calc. for $C_9H_{12}ClO_2P$: H, 5.53; P, 14.18%).

Ethyl methyl(chloromethyl)phosphinate 3b. This compound was prepared by method D (yield 79%), bp 48 °C/0.2 mmHg, δ_H 1.37 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 1.61 (3 H, d, $^2J_{PH}$ 17, MeP), 3.56 (2 H, d, $^2J_{PH}$ 9, PCH_2Cl), 4.14 (2 H, quin, $^3J_{HH} = {}^3J_{PH}$ = 7, MeCH_2O); δ_C 9.72 ($^3J_{CP}$ 103, MeP), 16.46 ($^3J_{CP}$ 6, *Me*CH_2O), 35.77 ($^1J_{CP}$ 96, PCH_2Cl), 61.25 ($^2J_{CP}$ 7, OCH_2Me) (Found: 156.0012. Calc for $C_4H_{10}ClO_2P$: 156.0101) (Found: C, 30.97; H, 6.39. Calc. for $C_4H_{10}ClO_2P$: C, 30.42; H, 6.52%).

Ethyl phenyl(1-chloroethyl)phosphinate 3c. This compound was prepared by method B (yield 48%), method C (yield 85%) or method D (yield 71%), bp 121 °C/0.2 mmHg; δ_H 1.37 and 1.38 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 1.63 and 1.64 (3 H, dd, $^3J_{PH}$ 16, $^3J_{HH}$ 7, CHCl*Me*), 4.16 (2 H, m, MeCH_2O), 4.2 (1 H, m, *CH*ClMe), 7.55–7.9 (5 H, m, Ph); δ_C 16.49 and 16.55 ($^3J_{CP}$ 6, *Me*CH_2O), 18.47 and 18.58 ($^2J_{CP}$ 16.84, CHCl*Me*), 48.96 and 49.88 ($^1J_{CP}$ 108, *PCH*ClMe), 62.11 and 61.91 ($^2J_{CP}$ 7, OCH_2Me), 126.91 ($^1J_{CP}$ 133, Ph, C_{ipso}), 128.6 ($^3J_{CP}$ 13, Ph, C_{meta}), 132.4 ($^2J_{CP}$ 9, Ph, C_{ortho}), 133 ($^4J_{CP}$ 0, Ph, C_{para}) (Found: 232.0420. Calc for $C_{10}H_{14}ClO_2P$: 232.0419) (Found: C, 51.49; H, 6.35; P, 12.72. Calc. for $C_{10}H_{14}ClO_2P$: C, 51.63; H, 6.07; P, 13.1%).

Ethyl phenyl(1-chloropropyl)phosphinate 3d. This compound was prepared by method B (yield 45%), method C (yield 85%) or method D (yield 76%), bp 134 °C/0.2 mmHg; δ_H 1.09 and 1.1 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2CHCl), 1.37 and 1.38 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 1.95 (2 H, m, MeCH_2CHCl), 3.87 (1 H, dm, $^2J_{PH}$ 11, $MeCH_2CHCl$), 4.16 (2 H, m, MeCH_2O), 7.52–7.9 (m, 5 H, Ph); δ_C 11.49 ($^3J_{CP}$ 12, *Me*CH_2CHCl), 16.49 and 16.55 ($^3J_{CP}$ 6, *Me*CH_2O), 24.88 ($^2J_{CP}$ 4, MeCH_2CHCl), 56.37 and 57.38 ($^1J_{CP}$ 107, $MeCH_2CHCl$), 61.78 and 62.0 ($^2J_{CP}$ 6, MeCH_2O), 127.4 ($^1J_{CP}$ 133, Ph, C_{ipso}), 128.8 ($^3J_{CP}$ 14, Ph, C_{meta}), 131.9 ($^2J_{CP}$ 7, Ph, C_{ortho}), 132.9 (Ph, C_{para}) (Found: C, 53.22; H, 6.40. Calc. for $C_{11}H_{16}ClO_2P$: C, 53.56; H, 6.54%).

Ethyl phenyl(1-chloroprop-2-enyl)phosphinate 3e. This compound was prepared by method B (yield 8%) and purified by use of a Kugelrhor; bp 110 °C/0.2 mmHg; δ_H 1.36 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 4.2 (2 H, m, MeCH_2O), 4.58 (1 H, m, *CH*Cl), 5.37 (2 H, m, CH=CH_2), 5.92 (1 H, m, *CH*=CH_2), 7.52–7.9 (5 H, m, Ph); δ_C 16.51 ($^3J_{CP}$ 7, *Me*CH_2O), 55.42 and 56.24 ($^1J_{CP}$ 105, *CH*Cl), 62.2 and 62.43 ($^2J_{CP}$ 6, MeCH_2O), 120.8 and 121.03 ($^2J_{CP}$ 11, *CH*=CH_2), 132.88 ($^3J_{CP}$ 16, CH=CH_2), 128.6–132.64 (Ph) (Found: 244.0417. Calc. for $C_{11}H_{14}ClO_2P$: 244.0419).

Ethyl phenyl(1-chlorobut-3-enyl)phosphinate 3f. This compound was prepared by method C (yield 85%); δ_H 1.37 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 2.57 (2 H, m, $CHClCH_2$), 3.98 (1 H, m, *CH*Cl), 4.14 (2 H, m, MeCH_2O), 4.58 (1 H, m, *CH*Cl), 5.07 (2 H, m, CH=CH_2), 5.81 (1 H, m, *CH*=CH_2), 7.52–7.82 (5 H, m, Ph); δ_C 15.7 ($^3J_{CP}$ 7, *Me*CH_2O), 34.8 ($CHCl\mathit{CH}_2$), 52.8 and 53.6 ($^1J_{CP}$ 106, *CH*Cl), 61.1 (MeCH_2O), 115.7 (*CH*=CH_2), 125.1 (CH=*C*H_2), 127.6–132.1 (Ph) (Found: 258.0418. Calc. for $C_{12}H_{16}ClO_2P$: 258.0419).

Ethyl phenyl(1-chlorobenzyl)phosphinate 3g. This compound was prepared by method B (yield 85%) or method D (yield 85%); mp 68 °C, (two diastereoisomers, ratio 85:15); major isomer: δ_H 1.34 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 4.15 (2 H, m, *CH*Cl), 4.97 (1 H, d, $^2J_{PH}$ 9, MeCH_2O), 7.5 (10 H, m, Ph); δ_C 16.53 ($^3J_{CP}$ 6, *Me*CH_2O), 57.08 ($^1J_{CP}$ 103, MeCH_2O), 62.6 ($^2J_{CP}$ 7, *CH*Cl), 126.8–133.68 (Ph); minor isomer: δ_H 1.26 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 4.15 (2 H, m, *CH*Cl), 5.0 (1 H, d, $^2J_{PH}$ 9, MeCH_2O), 7.5 (10 H, m, Ph); δ_C 16.53 ($^3J_{CP}$ 6, *Me*CH_2O), 56.39 ($^1J_{CP}$ 103, MeCH_2O), 62.58 ($^2J_{CP}$ 7, *CH*Cl), 126.8–133.68 (Ph) (Found: 270.0577. Calc. for $C_{13}H_{16}ClO_2P$: 270.0576) (Found: C, 57.77; H, 5.86; Cl, 12.5; P, 10.71. Calc. for $C_{13}H_{16}ClO_2P$: C, 57.68; H, 5.96; Cl, 13.1; P, 11.44%).

Ethyl methyl(1-chloroethyl)phosphinate 3h. This compound was prepared by method D (yield 78%), bp 58 °C/0.2 mmHg; δ_H 1.36 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 1.59 and 1.61 (3 H, d, $^2J_{PH}$ 14, MeP), 1.69 and 1.71 (3 H, dd, $^3J_{PH}$ 15, $^3J_{HH}$ 7, *Me*CHCl), 3.96 (1 H, m, PCHCl), 4.12 and 4.17 (2 H, quin, $^3J_{HH} = {}^3J_{PH}$ = 7,

MeCH_2O); δ_C 9.72 and 10.4 ($^1J_{CP}$ 99, MeP), 16.55 and 16.88 ($^3J_{CP}$ 6, *Me*CH_2O), 18.18 and 18.42 ($^2J_{CP}$ 17, *Me*CHCl), 49.85 and 48.64 ($^1J_{CP}$ 101, MeCHCl), 61.26 and 61.71 ($^2J_{CP}$ 7, OCH_2Me) (Found: C, 39.85; H, 6.45. Calc. for $C_6H_{12}ClO_2P$: C, 39.47; H, 6.62%).

Ethyl methyl(1-chloropropyl)phosphinate 3i. This compound was prepared by method D (yield 79%); δ_H 1.07 and 1.12 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2CHCl), 1.35 and 1.37 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 1.60 and 1.62 (3 H, d, $^2J_{PH}$ 15, MeP), 2.05 (2 H, m, MeCH_2CHCl), 3.98 (1 H, m, PCHCl), 4.21 (2 H, m, MeCH_2O); δ_C 9.21 and 9.9 ($^1J_{CP}$ 97, MeP), 11.83 and 12.14 ($^3J_{CP}$ 7, *Me*CH_2CHCl), 16.49 and 16.62 ($^3J_{CP}$ 6, *Me*CH_2O), 24.4 and 24.6 ($^2J_{CP}$ 2.7, Me*C*H_2HCl), 56.66 and 57.12 ($^1J_{CP}$ 101, *C*HCl), 61.19 and 61.36 ($^2J_{CP}$ 6, OCH_2Me) (Found: C, 43.01; H, 7.29. Calc. for $C_7H_{14}ClO_2P$: C, 42.76; H, 7.18%).

Synthesis of the (1-hydroxy)phosphinates 5

General procedure. Activated alumina (1–5% KF, see Table 1) was added to a mixture containing **4** (0.1 mol) and an aldehyde (0.11–0.35 mol), until complete adsorption had occurred. The mixture was left in the dark overnight at room temperature (see Table 2). The α-hydroxyphosphinates were then extracted with CH_2Cl_2 (4 × 60 ml). After elimination of the solvent under reduced pressure, the products (purity >95%) were either purified by distillation or used as obtained for further reactions. The ratio between diastereoisomers was determined by ^{31}P NMR (see Table 2).

Ethyl phenyl(1-hydroxyethyl)phosphinate 5a. Bp 81 °C/0.1 mmHg (two diastereoisomers, ratio 3:2); δ_H 1.22 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2OP), 1.33 [3 H, dd, $^3J_{HH}$ 7, $^3J_{PH}$ 16.5, *Me*CH(OH)], 3.98 [1 H, m, MeC*H*(OH)], 4.2 (2 H, dq, $^3J_{PH}$ 7, $^3J_{HH}$ 8, MeCH_2OP); 4.65 (1 H, s, OH), 7.38–7.72 (5 H, m, Ph); δ_C 16.51 ($^3J_{CP}$ 6, *Me*CH_2OP); 16.7 and 17.11 [$^3J_{CP}$ 3, *Me*CH(OH)], 61.41 and 61.56 ($^2J_{CP}$ 8, MeCH_2OP), 66.05 and 65.42 [$^1J_{CP}$ 118, Me*C*H(OH)], 128.5 ($^1J_{CP}$ 120, Ph, C_{ipso}), 128.5 ($^3J_{CP}$ 12, Ph, C_{meta}), 132.44 (Ph, C_{ortho}), 132.93 (Ph, C_{para}); ν_{max}/cm^{-1} 3360vs (OH), 1590w (C=C), 1435s (P–Ph), 1195vs (P=O), 1030s (P–O–C).

Ethyl phenyl(1-hydroxypropyl)phosphinate 5b. Bp 93 °C/0.1 mmHg (two diastereoisomers, ratio 3:2); δ_H 1.0 and 1.15 [3 H, t, $^3J_{HH}$ 7, *Me*CH_2CH(OH)], 1.32 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2OP), 1.62 [2 H, m, MeCH_2CH(OH)], 3.83 [1 H, m, MeCH_2-C*H*(OH)], 4.12 (2 H, dq, $^3J_{PH}$ 7, $^3J_{HH}$ 9, MeCH_2OP), 4.7 (1 H, s, O*H*), 7.5–7.75 (5 H, m, Ph); δ_C 10.44 and 10.51 [$^3J_{CP}$ 6, *Me*CH_2CH(OH)], 16.43 and 16.45 ($^3J_{CP}$ 6, *Me*CH_2OP), 23.71 and 24.15 [$^2J_{CP}$ 3, Me*C*H_2CH(OH)], 61.23 and 61.29 ($^2J_{CP}$ 11, Me*C*H_2OP), 70.93 and 71.41 [$^1J_{CP}$ 116, MeCH$_2$*C*H(OH)], 128.4 (Ph C_{ipso}), 128.5 ($^3J_{CP}$ 10, Ph C_{meta}), 132.33 (Ph, C_{ortho}), 132.5 (Ph, C_{para}); ν_{max}/cm^{-1} 3320vs (OH), 1595w (C=C), 1440s (P–Ph), 1200vs (P=O), 1035s (P–O–C).

Ethyl phenyl(1-hydroxybenzyl)phosphinate 5c. (Two diastereoisomers, ratio 1:1); δ_H 1.19 and 1.22 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2OP), 3.95 (2 H, quin, $^3J_{PH}$ = $^3J_{HH}$ 7, MeCH_2OP), 5.07 and 5.18 [1 H, d, $^2J_{PH}$ 9, PhC*H*(OH)], 5.55 (1 H, s, O*H*), 7.5 (10 H, m, Ph); δ_C 16.43 ($^3J_{CP}$ 6, *Me*CH_2OP), 61.66 and 61.71 ($^2J_{CP}$ 7, MeCH_2OP), 72.89 and 73.05 [$^1J_{CP}$ 113, Ph*C*H(OH)], 128.4–136.8 (Ph); ν_{max}/cm^{-1} 3280vs (OH), 1605w and 1595w (C=C), 1440s (P–Ph), 1215vs (P=O), 1035s (P–O–C).

Ethyl phenyl(1-hydroxyprop-2-enyl)phosphinate 5d. (Two diastereoisomers, ratio 1:1); δ_H 1.28 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2OP), 3.9 (1 H, m), 4.1 (2 H, dq, $^3J_{PH}$ 10, $^3J_{HH}$ 7, MeCH_2OP), 4.27 (1 H, dm, CH_2=C*H*), 4.3 (1 H, s, OH), 5.22 (2 H, m, CH_2=CH), 7.22 (5 H, m, Ph); ν_{max}/cm^{-1} 3270vs (OH), 1635w and 1590w (C=C), 1435s (P–Ph), 1215vs (P=O), 1030s (P–O–C) (Found: C, 55.62; H, 6.41. Calc. for $C_{10}H_{15}O_3P$: C, 56.07; H, 7.06%).

Ethyl phenyl(1-hydroxybut-2-enyl)phosphinate 5e. Purification at 110 °C/10^{-2} mmHg (Kugelrhor), yield 77%; δ_H 1.3 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2OP), 1.65 (3 H, m, *Me*CH=CH), 3.8 [1 H, m, C*H*(OH)], 4.1 (2 H, dq, $^3J_{PH}$ 10, $^3J_{HH}$ 7, MeCH_2OP), 4.5 (1 H, m, MeC*H*=CH), 4.8 (1 H, s, OH), 5.26 (1 H, m, MeCH=C*H*), 7.1 (5 H, m, Ph); ν_{max}/cm^{-1} 3260vs (OH), 1590w (C=C), 1435s (P–Ph), 1220vs (P=O), 1030s (P–O–C).

Ethyl methyl(1-hydroxyethyl)phosphinate 5f. Bp 63 °C/0.2 mmHg (two diastereoisomers, ratio 1:1); δ_H 1.3 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2OP), 1.33 and 1.48 [3 H, dd, $^3J_{PH}$ 3, $^3J_{HH}$ 7, *Me*CH(OH)], 1.44 and 1.46 (3 H, d, $^2J_{PH}$ = 13, MeP), 3.95 [1 H, m, MeC*H*(OH)], 4.07 and 4.1 (2 H, quin, $^3J_{PH}$ = $^3J_{HH}$ 7, MeCH_2OP), 4.77 (s, 1 H, OH); δ_C 9.25 and 10.4 ($^1J_{CP}$ 87, MeP), 16.4 and 17.1 (*Me*CH_2OP), 16.68 [$^3J_{CP}$ 4, *Me*CH(OH)], 61.0 and 61.1 (Me*C*H_2OP), 65.6 and 65.8 [$^1J_{CP}$ 111, Me*C*H(OH)]; ν_{max}/cm^{-1} 3300vs (OH), 1175vs (P=O), 1000s (P–O–C) (Found: C, 40.01; H, 8.12. Calc. for $C_5H_{13}O_3P$: C, 39.47; H, 8.61%).

Ethyl methyl(1-hydroxypropyl)phosphinate 5g. Bp 71 °C/0.2 mmHg (two diastereoisomers, ratio 3:2); major diastereoisomer: δ_H 0.96 [3 H, t, $^3J_{HH}$ 7, *Me*CH_2CH(OH)], 1.35 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2OP), 1.48 (3 H, d, $^2J_{PH}$ 14, MeP), 1.7 [2 H, m, MeCH_2CH(OH)], 3.67 [1 H, m, MeCH$_2$C*H*(OH)], 4.12 (2 H, quin, $^3J_{PH}$ = $^3J_{HH}$ = 7, MeCH_2OP), 4.56 (1 H, s, OH); δ_C 9.8 ($^1J_{CP}$ 93, MeP), 10.47 [$^3J_{CP}$ 6, *Me*CH_2CH(OH)], 16.85 ($^3J_{CP}$ 7, *Me*CH_2OP), 23.41 [$^2J_{CP}$ 3, Me*C*H_2CH(OH)], 60.81 ($^2J_{CP}$ 10, Me*C*H_2OP), 71.9 [$^1J_{CP}$ 115, MeCH$_2$*C*H(OH)]; minor diastereoisomer: δ_H 1.0 [3 H, t, $^3J_{HH}$ 7, *Me*CH_2CH(OH)], 1.35 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2OP), 1.5 (3 H, d, $^2J_{PH}$ 14, MeP), 1.7 [2 H, m, MeCH_2CH(OH)], 3.67 [1 H, m, MeCH$_2$C*H*(OH)], 4.14 (2 H, quin, $^3J_{PH}$ = $^3J_{HH}$ = 7, MeCH_2OP), 4.56 (1 H, s, OH); δ_C 10.4 ($^1J_{CP}$ 92, MeP), 10.6 [$^3J_{CP}$ 6, *Me*CH_2CH(OH)], 17.05 ($^3J_{CP}$ 6, *Me*CH_2OP), 23.92 [$^2J_{CP}$ 3, Me*C*H_2CH(OH)], 60.95 ($^2J_{CP}$ 9, Me*C*H_2OP), 72.6 [$^1J_{CP}$ 118, MeCH$_2$*C*H(OH)]; ν_{max}/cm^{-1} 3400vs (OH), 1180vs (P=O), 1035s (P–O–C).

Ethyl phenyl(trichloromethyl)phosphinate 8a

In a 250 ml three-necked round bottom flask, equipped with a dropping funnel, a gas inlet tube and a thermometer, CCl_4 (58 ml, 93 g, 0.6 mol) was heated to 60 °C and **7a** (0.2 mol) was added dropwise. The reaction was almost complete at the end of the addition. The mixture was then cooled to room temperature and excess CCl_4 was eliminated under reduced pressure. The product spontaneously crystallized in hexane. Yield 85%, mp 89–90 °C (hexane–diethyl ether); δ_H 1.41 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 4.46 (2 H, quin, $^3J_{HH}$ = $^3J_{PH}$ = 7, MeCH_2O), 7.55–8.02 (5 H, m, Ph); δ_P 24.48; δ_C 16.3 ($^3J_{CP}$ 5, *Me*CH_2O), 64.85 ($^2J_{CP}$ 7, Me*C*H_2O), 91.99 ($^1J_{CP}$ 112, MeP), 128.09–134.3 (Ph).

Ethyl methyl(trichloromethyl)phosphinate 8b

This compound was prepared in a similar manner to **8a**. However, we obtained a mixture of MeP(O)(OEt)$_2$ and **8b** in a 3:7 ratio as determined by ^{31}P NMR. These compounds were separated by fractional distillation with the use of an efficient column. The desired product was obtained in 40% yield, bp 130–132 °C/16 mmHg; δ_H 1.37 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 1.83 (3 H, d, $^3J_{PH}$ 15, MeP), 4.36 (2 H, dq, $^3J_{HH}$ 7, $^3J_{PH}$ 10, MeCH_2O); δ_P 36.75.

Ethyl phenyl(3-chloroprop-1-enyl)phosphinate 10a

This compound was obtained by chlorination of **5d** using $SOCl_2$, followed by an allylic rearrangement (one isomer). Yield 75%; δ_H 1.33 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 4.0 (2 H, m, MeCH_2O), 4.15 (2 H, dd, $^3J_{HH}$ 5, $^4J_{PH}$ 2, CH_2ClCH=), 6.18 (1 H, dd, CH=C*H*P, *J* 20 and 17; these values correspond to the $^3J_{HHtrans}$ and $^2J_{PH}$ coupling constants. They are, however, too close to allow their attribution), 6.82 (1 H, dm, $^3J_{HH}$ 20, C*H*=CHP), 7.45–7.81 (5 H, m, Ph); δ_P 29.56; δ_C 16.46 ($^3J_{CP}$ 7, *Me*CH_2O), 43.95 ($^3J_{CP}$ 22, *C*H_2ClCH=CH), 60.93 ($^2J_{CP}$ 6, Me*C*H_2O), 124.1 ($^1J_{CP}$ 135, CH=*C*HP), 144 ($^2J_{CP}$ 6, *C*H=CHP) (Found: 244.0420. Calc. for $C_{11}H_{14}ClO_2P$: 244.0419).

Ethyl (3-chlorobut-1-enyl)phenylphosphinate 10b

This compound was obtained by chlorination of **5e** using $SOCl_2$, followed by an allylic rearrangement (two diastereo-

isomers, ratio 1:1). Yield 75%; δ_H 1.32 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 1.6 (3 H, d, $^3J_{HH}$ 7, *Me*CHCl), 4.05 (2 H, dq, $^3J_{HH}$ 7, $^3J_{PH}$ 10, MeCH_2O), 4.6 (1 H, m, C*H*ClCH=), 6.1 (1 H, dd, $^3J_{HHtrans}$ 20, $^2J_{PH}$ 15, CH=C*H*P), 6.75 (1 H, m, $^3J_{HH}$ 20, $^3J_{PH}$ 16, C*H*=CHP), 7.5–7.75 (5 H, m, Ph); δ_P 26.31 and 26.46; δ_C 16.48 ($^3J_{CP}$ 7, *Me*CH_2O), 24.13 (*Me*CHCl), 56.03 ($^3J_{CP}$ 21, *C*HClCH=CH), 61.14 ($^2J_{CP}$ 6, MeCH_2O), 121.95 ($^1J_{CP}$ 135, CH=*C*HP), 150.52 ($^2J_{CP}$ 5, *C*H=CHP), 128.8–132.51 (Ph) (Found: 258.0580. Calc for $C_{12}H_{16}ClO_2P$: 258.0576).

Ethyl (1-chloromethyl)phosphonochloridate 12a[20]

[$(CH_2Cl)P(O)(OEt)_2$] **11a**[7] (0.1 mol) and freshly distilled $POCl_3$ (0.11 mol) were placed in a 50 ml flask under a dry atmosphere of nitrogen. The mixture was heated to 70 °C for 3 h. The compound **12a** was purified by distillation, $(EtO)POCl_2$ (bp 32 °C/0.2 mmHg) and excess of $POCl_3$ were eliminated in the first fraction. Yield 82%, bp 48 °C/0.2 mmHg; δ_H 1.45 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 3.95 (2 H, d, $^2J_{PH}$ 9, PCH_2Cl), 4.37 (2 H, dq, $^3J_{PH}$ 10, $^3J_{HH}$ 7, MeCH_2O); δ_P 30.48; δ_C 16 ($^3J_{CP}$ 7, *Me*CH_2O), 38.85 ($^1J_{CP}$ 144, P*C*H_2Cl), 65.26 ($^2J_{CP}$ 8, Me*C*H_2O).

Ethyl (1-chloroethyl)phosphonochloridate 12b[20]

This compound was prepared from [(MeCHCl)P(O)$(OEt)_2$] **11b**[7] in a similar manner as for **12a**. Yield 85%, bp 52 °C/0.2 mmHg, (two diastereoisomers, ratio 1:1); δ_H 1.42 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 1.76 (3 H, dd, $^3J_{PH}$ 21, $^3J_{HH}$ 7, PCHCl*Me*), 4.15 (1 H, m, PCHCl), 4.37 (2 H, dq, $^3J_{PH}$ 10, $^3J_{HH}$ 7, MeCH_2O); δ_P 36.18 and 36.87; δ_C 15.98 ($^3J_{CP}$ 6, *Me*CH_2O), 19.00 and 19.02 ($^2J_{CP}$ 5, PCHCl*Me*), 51.01 and 51.28 ($^1J_{CP}$ 143, P*C*HCl), 65.32 ($^2J_{CP}$ 9, Me*C*H_2O).

Ethyl 1-chloropropylphosphonochloridate 12c

This compound was prepared from [(EtCHCl)P(O)$(OEt)_2$] **11c**[7] in a similar manner as for **12a**. Yield 74%, bp 64 °C/0.2 mmHg, (two diastereoisomers, ratio 3:2); δ_H 1.2 (3 H, t, $^3J_{HH}$ 7, $CHClCH_2$*Me*), 1.43 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 2.17 (2 H, m, $CHClCH_2$), 4.37 (2 H, dq, $^3J_{PH}$ 10, $^3J_{HH}$ 7, MeCH_2O), 5.02 (1 H, m, C*H*$ClCH_2$); δ_P 34.7 (major isomer) and 35.5 (minor isomer); δ_C 10.73 and 10.9 ($^3J_{CP}$ 5, $CHClCH_2$*Me*), 16.24 and 16.58 ($^3J_{CP}$ 6, *Me*CH_2O), 23.93 and 24.26 ($^2J_{CP}$ 2, $CHClCH_2$), 58.9 and 59.31 ($^1J_{CP}$ 146, P*C*HCl), 65.72 and 66.13 ($^2J_{CP}$ 9, Me*C*H_2O) (Found: 203.9870. Calc. for $C_5H_{11}Cl_2O_2P$: 203.9874).

Ethyl 1-chlorobenzylphosphonochloridate 12d

This compound was prepared from [(PhCHCl)P(O)$(OEt)_2$] **11d**[7] in a similar manner as for **12a**, excepted that the reaction mixture was heated to 65 °C for 5 h (two diastereoisomers, ratio 1:1). Yield 80%; δ_H 1.25 (3 H, t, $^3J_{HH}$ 7, *Me*CH_2O), 4.27 (2 H, dq, $^3J_{PH}$ 10, $^3J_{HH}$ 7, MeCH_2O), 5.15 (1 H, 2, $^2J_{PH}$ 11, C*H*ClPh), 7.43–7.8 (5 H, m, Ph); δ_P 32.5 and 33.3; δ_C 15.7 ($^3J_{CP}$ 8, *Me*CH_2O), 57.77 and 58.19 ($^1J_{CP}$ 149, P*C*HCl), 65.66 ($^2J_{CP}$ 7, Me*C*H_2O), 128.67–130.46 (Ph) (Found: 251.9872. Calc. for $C_9H_{11}Cl_2O_2P$: 251.9874).

Diethyl 1-methyl-1-chloroethylphosphinate 13

In a 500 ml three-necked round bottom flask, equipped with a mechanical stirrer, a dropping funnel, a gas inlet tube and a thermometer were placed [(MeCHCl)P(O)$(OEt)_2$] **11b**[7] (8.3 g, 4.14×10^{-2} mol) and LiCl (0.88 g, 2.07×10^{-2} mol) in freshly distilled THF (150 ml). The solution was cooled to −85 °C (internal temperature) and BuLi (4.14×10^{-2} mol) was then carefully added dropwise, so that the temperature did not rise above −80 °C. After the reaction mixture had been stirred at −85 °C for a few minutes, MeI (3.1 ml, 5×10^{-2} mol) was added. The mixture was then allowed to warm to room temperature and then neutralized with 0.5 M HCl. After it had settled the aqueous layer was washed with CH_2Cl_2 (2 × 40 ml). The organic fractions were combined, dried over $MgSO_4$ and the solvent removed under reduced pressure. After distillation of the residue, **13** was obtained. Yield 81%, bp 66 °C/0.2 mmHg; δ_H 1.38 (6 H, t, ^3J_H 7, *Me*CH_2O), 1.72 (6 H, d, $^3J_{PH}$ 15, Me_2CCl), 4.22 (4 H, quin, $^3J_{PH} = {}^3J_{HH} = 7$, MeC$H_2$O); δ_P 23.62; δ_C 16.48 ($^3J_{CP}$ 6, *Me*CH_2O), 28.12 ($^2J_{CP}$ 13, Me_2CCl), 60.73 ($^1J_{CP}$ 163, Me_2CCl), 63.8 ($^2J_{CP}$ 7, MeCH_2O) (Found: C, 39.71; H, 7.20. Calc. for $C_7H_{16}ClO_3P$: C, 39.17; H, 7.51%).

Ethyl 1-methyl-1-chloroethylphosphonochloridate 14

This compound was prepared by treatment of **13** with $POCl_3$ following the procedure described above. Yield 73%, bp 54 °C/0.1 mmHg; δ_H 1.4 (3 H, t, ^3J_H 7, *Me*CH_2O), 1.78 (6 H, d, $^3J_{PH}$ 19, Me_2CCl), 4.22 (2 H, dq, $^3J_{PH}$ 10, $^3J_{HH}$ 7, MeCH_2O); δ_P 40.22; δ_C 16.02 ($^3J_{CP}$ 6, *Me*CH_2O), 27.49 ($^2J_{CP}$ 13, Me_2CCl), 63.7 ($^1J_{CP}$ 142, Me_2CCl), 65.28 ($^2J_{CP}$ 9, MeCH_2O) (Found: 203.9860. Calc. for $C_5H_{11}Cl_2O_2P$: 203.9874).

Ethyl methyl(1-methyl-1-chloroethyl)phosphinate 15

This compound was prepared by the use of method D (yield 74%), bp 86 °C/0.4 mmHg; δ_H 1.36 (3 H, t, ^3J_H 7, *Me*CH_2O), 1.6 (3 H, d, $^2J_{PH}$ 14, MeP), 1.73 (6 H, d, $^3J_{PH}$ 15, Me_2CCl), 4.25 (2 H, quin, $^3J_{PH} = {}^3J_{HH} = 7$, MeC$H_2O$); δ_P 53.12; δ_C 8.8 ($^1J_{CP}$ 98, MeP), 16.42 ($^3J_{CP}$ 6, *Me*CH_2O), 27.95 ($^2J_{CP}$ 2, Me_2CCl), 60.85 ($^1J_{CP}$ 156, Me_2CCl), 63.68 ($^2J_{CP}$ 7, MeCH_2O) (Found: C, 38.35; H, 7.26. Calc. for $C_6H_{14}ClO_2P$: C, 39.04; H, 7.64%).

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