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Synthesis and Reactivity of α- and β-Chloro-α-phenylselanyl Esters

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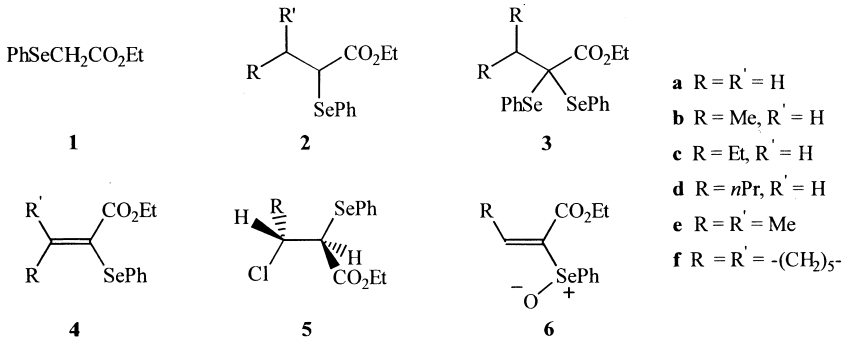
Abstract—Thermal decomposition of the dichloro-adducts derived from α-phenylselanylesters **1**, **2** and **4** has been studied. *N*-Chlorosuccinimide treatment of esters **2** was an efficient preparative method for α-chloro-α-phenylselanylesters **10** and α-chloro-α,β-unsaturated esters **11**. Some transformations of esters **10** were achieved. α,β-Dichloro-α-phenylselanylesters **22** were prepared from β-chloro-α-phenylselanylesters **5** or by decomposition of the dichloroselenuranes **21** derived from esters **4**.

In the preceding paper,[1] we described some observations relative to the reactivity of selenium-stabilized ester enolates derived from α-phenylselanyl esters **1** and **2**. Selenenylation of these intermediates has allowed the synthesis of bis(α-phenylselanyl)esters **3** allowing the access to the α,β-unsaturated esters **4** also prepared by dehydrochlorination of β-chloro-α-phenylselanyl esters **5** (R′=H).[2] The more stable *Z*-isomers of **4** (R′=H) were oxidized into *E*-vinylselenoxides **6** with opposite stereochemistry (Scheme 1).

Chlorination of these esters was carried out in continuation of previous works. The reaction of α-selenanyl carbonyl compounds,[3–6] functionalized allylic[7,8] and propargylic selenides[9] with sulfuryl chloride or bromine, has already been investigated. This paper presents results relative to the reaction of esters **1**, **2** and **4** with sulfuryl chloride or *N*-chlorosuccinimide allowing access to various α-chloro, β-chloro and α,β-dichloroesters.

The reaction of selenides with bromine, chlorine (or sulfuryl chloride) gives dihaloselenium adducts (dihaloselenuranes).[10] These tetracoordinated selenium compounds are described as molecular complexes or trigonal bipyramidal structures according to the nature of the halogen and the substituents.[11] The very unstable dibromoselenuranes derived from simple selenides decompose spontaneously with formation of alkyl bromide and benezeneselenenyl bromide.[12] The dichloro-adducts are more stable and can be isolated in several cases, as in the reactions of $PhSeCl_3$ with enolizable ketones and of sulfuryl chloride with α-phenylselanyl ketones or aldehydes.[4–6] When two alkyl groups are present on the α-carbon, the adduct decomposes, at room temperature with formation of α-chloroketone[5] or α-chloroaldehyde.[5,6] Other stable dichloroselenuranes were decomposed on heating to the corresponding alkyl chlorides and PhSeCl[13] or by treatment with pyridine for the access to α-chloroketones.[3b]



Scheme 1.

Keywords: α-chloro-α-phenylselanyl esters; selenide; dichloro-adducts; ^{1}H NMR; ^{13}C NMR.

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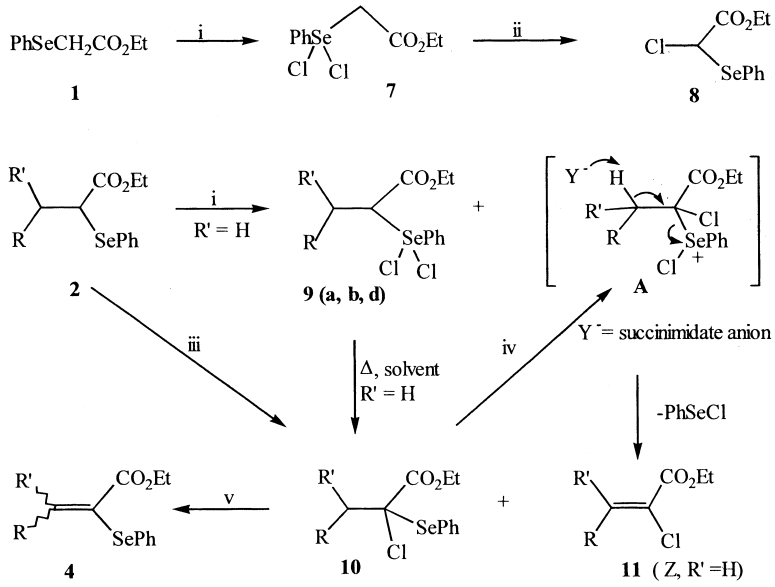


Scheme 2. (i) SO_2Cl_2, hexane, −30°C. (ii) Pyridine, CH_2Cl_2, Δ, 3 h (**8/1**:74/26). (iii) *N*-Chlorosuccinimide (1.2 equiv.), CCl_4, Δ, 2 h. (iv) *N*-Chlorosuccinimide (2.1 equiv.), CCl_4, Δ, 2 h. (v) LiBr, Li_2CO_3, THF, Δ, 4 h.

Table 1. Thermal decomposition of the dichloro-adduct **9d**

Solvent reflux 3 h	Product ratios		
	2d	**10d**	**11d**
THF	10	50	40
CCl_4	10	45	45
Toluene	35	30	35
1,2-Dichloroethane	10	70	20

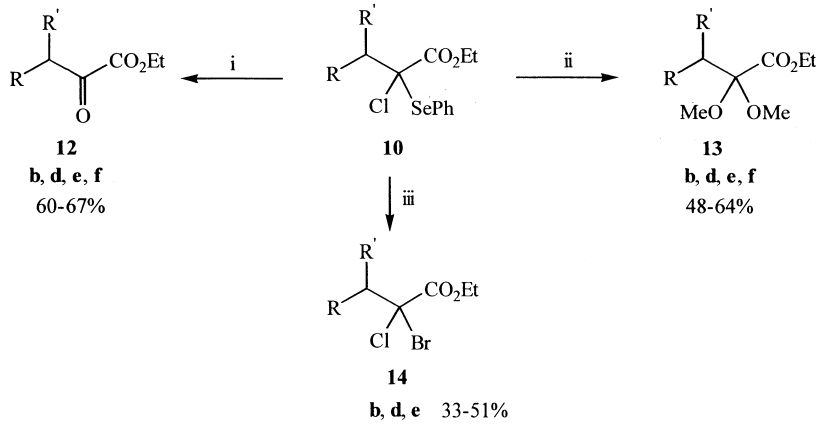
Treatment of ethyl phenylselanylacetate **1** with sulfuryl chloride, in hexane at −30°C, afforded instantaneously the dichloro-adducts **7**. In the presence of pyridine,[3b] decomposition of **7** gave a mixture of ethyl α-chloro-α-phenylselanylacetate **8**[14,15] and ester **1** (**8/1**:74/26). Esters **2a**, **2b**, **2d** gave also quantitatively the dichloroselenuranes **9** (Scheme 2). Unfortunately, they were totally recovered after pyridine treatment in CH_2Cl_2. The thermal decomposition was carried out in some solvents. According to the temperature and the reaction time, various ratios of α-phenylselanylester **2**, α-chloro-α-phenylselanylester **10** and α-chloro-α,β-unsaturated ester **11** were observed (Scheme 2). The product distributions relative to the decompositions of **9d** are assembled in Table 1.

Formation of the unsaturated α-chloro esters **11** cannot be avoided and the best result was obtained in 1,2-dichloroethane at reflux (70% of **10d**). The chloroester **8**[14,15] and its sulfur analog[15] were previously prepared by *N*-chlorosuccinimide treatment of the corresponding α-chalcogenyl ester in CCl_4 at room temperature. The NBS α-bromination was also achieved on ester **1** under the same conditions.[15] Applied to esters **2**, this method has led to poor results. The α-chloro-α-phenylselanyl ester **10** was always contamined with the corresponding α-chloroester **11**, apparently formed by a formal benzeneselenol elimination from **10**. In fact, this reaction could be explained by a three step sequence: NCS chlorination of the selenium atom of **10**, succinimidate β-deprotonation associated with PhSeCl elimination on the intermediate A (Scheme 2). Better results were observed when *N*-chlorosuccinimide (1.2 equiv.) was added by portions to a refluxing CCl_4 solution of **2**. The α-chloro-α-phenylselanyl esters **10** were the major products but the formation of **11** cannot be avoided (Table 2). The stable esters **11** were isolated in a pure form after distillation or silica gel chromatography. Esters **10**, however, were never obtained with an analytical purity. We have checked that the reaction of ester **2** (**b**, **d**, **f**) with two molar equivalents of NCS provided the corresponding α-chloroesters **11** in good

Table 2. NCS chlorination of selanylesters **2**

Entry no.	Substrate			Products (yield %)		Dehydrochlorination	
	No.	R	R′	**10**[a]/**11**	**11**[b]	4[c] (Yield %)	*E*/*Z*
1	**2a**	H	H	86/14 (10)[d]			
2	**2b**	Me	H	82/18 (14)	84		
3	**2c**	Et	H	77/23 (21)		57	33/67
4	**2d**	nPr	H	77/23 (22)	84	52	30/70
5	**2e**	Me	Me	88/12 (9)		56	
6	**2f**	$-CH_2)_5-$		75/25 (17)	91	55	

[a] Not isolated in a pure form.
[b] 2 equiv. of NCS.
[c] Overall yield from **2**.
[d] Isolated yield of **11** from **10/11** mixtures.



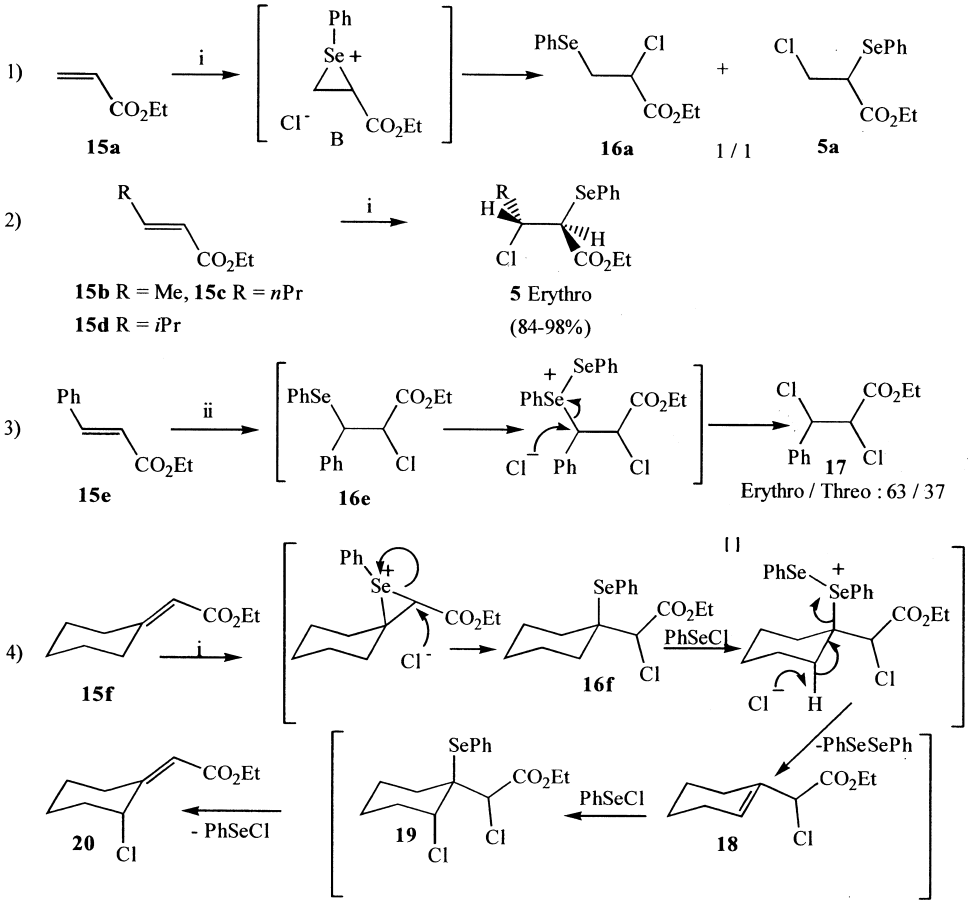
Scheme 3. (i) $Hg(OAc)_2$, acetone, H_2O, RT, 1 h. (ii) $Hg(OAc)_2$, MeOH, H_2O, RT, 24 h. (iii) *N*-Bromosuccinimide (1.2 equiv.), CCl_4, Δ, 2.5 h.

yields (Table 2). The *Z*-stereochemistry of these compounds was assigned according to the known structure of **11d**.[16]

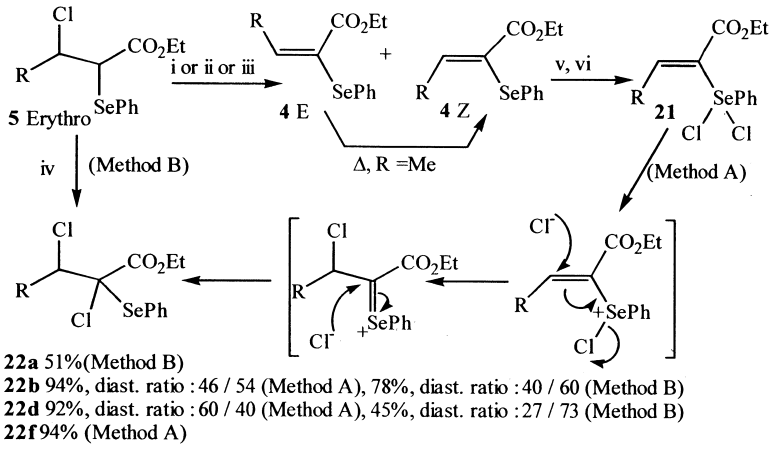
Dehydrochlorination of the crude α-chloro-α-phenylselanylesters **10** was then studied. Several bases and experimental conditions were tested without success. The synthesis of the unsaturated α-phenylselanyl esters **4b**, **4d**, **4e** and **4f** was however achieved with correct yields by treatment of **10** with LiBr and Li_2CO_3 in refluxing THF[17] (Table 2).

As for the synthesis of α-diketones from α-chloro-α-sulfanyl ketones,[18] we were able to prepare α-ketoesters **12** (**b**, **d**, **e**, **f**) by mercuric acetate hydrolysis of the α-chloro-α-phenylselanyl esters **10** (Scheme 3). Dimethyl acetals **13** were obtained by the same reaction achieved in methanol (48–64% yields). NBS treatment of esters **10**, in refluxing CCl_4, has allowed the formation of α-bromo-α-chloroesters **14b**, **14d** and **14e**, although isolated in poor yields. To our knowledge, **14b** is the only mixed α,α-dihaloester described.[16]

One goal of this work was to study the synthesis and the reactivity of α-phenylselanyl-α,β-unsaturated esters **4**



Scheme 4. (i) PhSeCl (1.5 equiv.), $ZnCl_2$ (1 equiv.), CH_2Cl_2, RT, 1.5 h. (ii) PhSeCl (2 equiv.), $ZnCl_2$ (1 equiv.), CH_2Cl_2, Δ, 17 h (75% yield).



Scheme 5. (i) Et_3N, benzene Δ, 5 h. (ii) K_2CO_3, acetone, Δ, 6 h. (iii) DBU, THF, RT, 20 h. (iv) *N*-Chlorosuccinimide (1 equiv.), CCl_4, Δ, 2 h. (v) SO_2Cl_2, light petroleum, −40°C, 10 mn. (vi) $CHCl_3$ or benzene, RT.

already described in the preceeding paper.[1] Dehydrochlorination of α-chloro-α-phenylselanyl esters **10** was found to be an efficient method. The same transformation can be achieved on β-chloro-α-phenylselanyl esters **5**. Addition of PhSeCl or PhSeBr to methyl acrylate or methyl crotonate in CH_2Cl_2 or CH_3CN was first investigated by Viehe et al.[19] With methyl acrylate, the two regioisomers were formed and the reaction occurred more slowly with methyl crotonate. It was recently observed[2a] that the addition can be activated in the presence of $ZnCl_2$. The regioselective formation of the β-chloro-α-phenylselanylester was the result of a *trans*-addition process. Without $ZnCl_2$, the reaction of PhSeCl with ethyl acrylate **15a** led to a 33/67 mixture of **16a** and **5a**[20] after 60 h at room temperature.

A more complete study of this reaction was carried out on unsaturated ethyl esters **15** (Scheme 4). A 1/1 mixture of the two regioisomers **16a** and **5a** was obtained from ethyl acrylate **15a**, PhSeCl (1.0 equiv.) and $ZnCl_2$ (1 equiv.) in CH_2Cl_2. Applied to *E*-esters **15b**, **15c** and **15d**, the erythro β-chloro-α-phenylselanylester **5** was the major isomer formed. A comparable result was observed with methyl cinnamate.[2a] We have found, however, that the dichloroester **17** was already formed at room temperature. Using two molar equivalents of PhSeCl in refluxing CH_2Cl_2, a 63/37 erythro/threo mixture of diastereoisomers was isolated. The substitution of the PhSe group, after phenylselanyl activation,[13a] occurs probably more efficiently at the benzylic position of the kinetic addition product **16e** (Scheme 4, reaction 3).

Isolation of ethyl 2-chlorocyclohexylideneacetate **20** from the reaction of ethyl cyclohexylideneacetate **15f** with PhSeCl was more surprising (Scheme 4, reaction 4). We suggest that the addition product **16f** could be activated by a second molecule of reagent, allowing diphenyldiselenide and HCl eliminations with formation of the allylic chloride **18**. A regioselective PhSeCl addition must afford the α,γ-dichloro-β-phenylselanylester **19**. A subsequent elimination of PhSeCl, as already observed for chlorine or bromine addition to γ-phenylselanyl-α,β-unsaturated esters,[7] could explain the formation of the conjugated double bond.

Scheme 5 assembles some reactions carried out on β-chloro-α-phenylselanyl esters **5**. In the preceding paper,[1] three methods were described for the preparation of α-phenylselanyl-α,β-unsaturated esters **4**. We have observed a *E*→*Z* isomerization on heating.

α-Selanylesters **4b**, **4d** and **4f** were treated with sulfuryl chloride. The corresponding dichloro-adducts **21** were instantaneously formed at −40°C in light petroleum and decomposed at room temperature. α,β-Dichloro-α-phenylselanyl esters **22** were isolated in a pure form with quite quantitative yields (method A). The stereochemistry of **22b** (R=Me) and **22d** (R=*n*Pr) was not assigned. The mechanism proposed in Scheme 5 explains the transformation of the unsaturated dichloroselenuranes **21** into dichloro addition products **22**. These esters were also prepared, in fair to good yields, by *N*-chlorosuccinimide treatment of β-chloro-α-phenylselanyl esters **5** (Erythro) on heating in CCl_4 (method B), **22b** and **22d** being isolated as diastereoisomeric mixtures.

This work has shown that α-phenylselanyl esters **1** and **2** give stable dichloro-adducts **7** and **9**. The thermal decomposition of **9** has provided α-chloro-α-phenylselanyl esters **10** leading to α-chloro-α,β-unsaturated esters **11** by *N*-chlorosuccinimide treatment. Esters **10** are also good substrates for the access to α-oxoesters **12**, dimethyl acetals **13** and α-bromo-α-chloro esters **14**. PhSeCl addition on α,β-unsaturated esters **15** afforded erythro β-chloro-α-phenylselanyl esters **5**. Dehydrochlorination of esters **5** has opened a new route to α,β-unsaturated-α-phenylselanyl esters **4**. The thermal decomposition of the dichloro-adducts **21**, derived from esters **4**, and the NCS treatment of esters **5** have allowed the synthesis of α,β-dichloro-α-phenylselanylesters **22**.

Experimental

α-Phenylselanylesters **1** and **2**, were described in the preceding paper.[1] α,β-Unsaturated esters **15d**[21] and **15f**,[22] not commercially available, were prepared by Wittig–Horner reaction using triethyl phosphonoacetate, *n*-butyllithium, isobutyraldehyde for **15d** and cyclohexanone

for **15f**. The solvents were distilled before use and light petroleum refers to the fraction with bp 40–60°C. GC/mass spectrometry analysis was performed on a Hewlett–Packard HP5890 with an HP-1 capillary column (25 m, 0.22 mm, He carrier gas) at 70 eV. ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$ on a Brucker AC200 spectrometer. C, H microanalysis were determined with a Carlo-Erba 1106 analyzer.

α-Phenylselanylesters dichloro-adducts (general procedure)

Sulfuryl chloride (0.135 g, 1 mmol) was slowly added to a solution of ester **1** or **2** (1 mmol) in light petroleum (5 ml) at −40°C. The mixture was stirred for 10 min at the same temperature. The solid was washed three times with the same solvent at low temperature and dried under argon. Compounds **7** and **9** can be stored several days, without appreciable decomposition at −4°C.

Ethyl phenylselanylacetate dichloro-adduct 7. (92% yield). ^{1}H NMR δ: 7.93–7.98 (2H, m), 7.51–7.56 (3H, m), 4.95 (2H, s), 4.39 (2H, q, J=7.0 Hz), 1.37 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 163.8, 139.4, 131.8, 130.0, 129.4, 65.2, 63.6, 13.9. IR (cm^{-1}): 3055, 1736, 1581. Anal. Calcd for $C_{10}H_{12}O_2Cl_2Se$: C, 38.24; H, 3.85. Found: C, 38.34; H, 3.77.

Ethyl 2-phenylselanylpropanoate dichloro-adduct 9a. (95% yield). ^{1}H NMR δ: 8.08–8.14 (2H, m), 7.48–7.55 (3H, m), 5.21 (1H, q, J=7.0 Hz), 4.27 (2H, m), 1.90 (3H, d, J=7.3 Hz), 1.20 (3H, t, J=7.0 Hz). IR (cm^{-1}): 3058, 1734, 1580. Anal. Calcd for $C_{11}H_{14}O_2Cl_2Se$: C, 40.27; H, 4.30. Found: C, 40.32; H, 4.27.

Ethyl 2-phenylselanylbutanoate dichloro-adduct 9b. (91% yield). ^{1}H NMR δ: 8.04–8.12 (2H, m), 7.46–7.51 (3H, m), 4.89 (1H, dd, J=3.5, 10.3 Hz), 4.18 (2H, q, J=7.2 Hz), 2.55–2.10 (2H, m), 1.16 (3H, t, J=7.0 Hz), 1.08 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 165.6, 138.3, 131.6, 131.1, 129.2, 75.9, 62.6, 22.5, 13.5, 13.2. IR (cm^{-1}): 3061, 1731, 1580. Anal. Calcd for $C_{12}H_{16}O_2Cl_2Se$: C, 42.13; H, 4.71. Found: C, 42.25; H, 4.82.

Ethyl 2-phenylselanylhexanoate dichloro-adduct 9d. (91% yield). ^{1}H NMR δ: 8.07–8.12 (2H, m), 7.46–7.52 (3H, m), 4.93 (1H, dd, J=3.2, 10.1 Hz), 4.18 (2H, dq, J=1.5, 7.1 Hz), 2.40 (1H, m), 2.15 (1H, m) 1.65–1.15 (4H, m), 1.08 (3H, t, J=7.0 Hz), 0.88 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 165.6, 138.2, 131.6, 131.2, 129.2, 74.6, 62.6, 30.5, 28.2, 22.1, 13.5. IR (cm^{-1}): 3061, 1739, 1579. Anal. Calcd for $C_{14}H_{20}O_2Cl_2Se$: C, 45.42; H, 5.45. Found: C, 45.68; H, 5.59.

α-Chloro-α-phenylselanyl esters 8 and 10 (general procedure)

N-Chlorosuccinimide (0.163 g, 1.2 mmol) was added, in small portions over a period of 20 min, to a solution of ester **2** (1 mmol) in CCl_4 (15 ml) at reflux. The mixture was stirred for 2 h, cooled at −20°C, filtered and evaporated without heating. Succinimide was precipitated by addition of pentane before complete evaporation. After filtration and concentration, the residue was extracted three times with pentane and filtered. The organic layer was concentrated and the oily residue was rectified by Kugelrohr distillation. The chloroesters **10** were never obtained in an analytical purity even after silica gel chromatography. They are however pure enough to be used for further reactions. The unsubstituted α-chloroester **8** was prepared, by the same procedure, from ester **1**.

Ethyl chloro (phenylselanyl)acetate 8.[14,15] ^{1}H NMR δ: 7.61–7.67 (2H, m) 7.26–7.40 (3H, m), 5.49 (1H, s), 4.15 (2H, q, J=7.0 Hz), 1.20 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 163.7, 131.9, 130.0, 129.4, 65.3, 63.7, 13.9. IR (cm^{-1}): 3058, 1745, 1577.

Ethyl 2-chloro-2-phenylselanylpropanoate 10a.[23] ^{1}H NMR δ: 7.64–7.70 (2H, m), 7.30–7.43 (3H, m), 4.13 (2H, q, J=7.0 Hz), 2.03 (3H, s), 1.19 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 166.0, 137.5, 129.9, 128.9, 127.4, 62.6, 30.4, 13.8. IR (cm^{-1}): 3058, 1725, 1580. MS: M^+=292.

Ethyl 2-chloro-2-phenylselanylbutanoate 10b. ^{1}H NMR δ: 7.61–7.67 (2H, m), 7.30–7.42 (3H, m), 4.09 (2H, q, J=7.0 Hz), 2.26 (2H, m), 1.16 (3H, t, J=7.0 Hz), 1.08 (3H, t, J=7 Hz). ^{13}C NMR δ: 168.0, 137.5, 129.8, 128.8, 71.6, 62.5, 34.9, 13.8, 10.3. IR (cm^{-1}): 3058, 1725, 1577. MS: M^+=306.

Ethyl 2-chloro-2-phenylselanylhexanoate 10d. ^{1}H NMR δ: 7.61–7.68 (2H, m), 7.30–7.40 (3H, m), 4.07 (2H, q, J=7.0 Hz), 2.25 (2H, m), 1.42–1.20 (4H, m), 1.15 (3H, t, J=7.0 Hz), 0.88 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 168.3, 137.5, 129.9, 128.8, 70.9, 62.4, 41.2, 27.9, 22.2, 13.8. IR (cm^{-1}): 3058, 1728, 1575. MS: M^+=334.

Ethyl 2-chloro-3-methyl-2-phenylselanylbutanoate 10e. ^{1}H NMR δ: 7.60–7.67 (2H, m), 7.26–7.40 (3H, m), 3.95 (2H, q, J=7.0 Hz), 2.72 (1H, m), 1.28 (3H, d, J=6.6 Hz). 1.08 (3H, t, J=7.0 Hz), 0.96 (3H, t, J=6.6 Hz). ^{13}C NMR δ: 168.0, 137.4, 129.8, 128.9, 78.8, 62.2, 36.9, 18.4, 18.3, 13.7. IR (cm^{-1}): 3058, 1722, 1577. MS: M^+=320.

Ethyl α-chloro-α-cyclohexyl phenylselanylacetate 10f. ^{1}H NMR δ: 7.60–7.68 (2H, m), 7.22–7.42 (3H, m), 3.94 (2H, q, J=7.0 Hz), 2.42–1.12 (11H, m) −1.07 (3H, t, J=7.1 Hz). ^{13}C NMR δ: 163.6, 131.1, 130.7, 128.9, 127.5, 63.4, 61.3, 49.6, 32.6, 31.8, 27.6, 27.1, 25.8, 13.9. IR (cm^{-1}): 3060, 1720, 1578. MS: M^+=360.

α-Chloro-α,β-unsaturated esters 11 (general procedure)

The phenylselanylester **2** (1 mmol) was added to a suspension of *N*-chlorosuccinimide (0.286 g, 2.1 mmol) in CCl_4 (5 ml). The mixture was stirred under reflux for 4 h, concentrated under reduced pressure. The purification was achieved by Kugelrohr distillation. The three chloroesters are known compounds. The *Z* stereoisomer of **11b** and **11d** were only formed.

***Z*-Ethyl 2-chlorobut-2-enoate 11b.**[24] (84% yield). ^{1}H NMR δ: 7.11 (1H, q, J=7.0 Hz), 4.22 (2H, q, J=7.2 Hz), 1.90 (3H, d, J=7.2 Hz), 1.28 (3H, t, J=7.0 Hz).

***Z*-Ethyl 2-chlorohex-2-enoate 11d.**[16] (84% yield). ^{1}H NMR δ: 7.01 (1H, q, J=7.2 Hz), 4.21 (2H, q, J=7.2 Hz), 2.27 (2H, q, J=7.2 Hz), 1.46 (2H, m), 1.27 (3H, t, J=7.2 Hz), 0.90 (3H,t, J=7.2 Hz). ^{13}C NMR δ: 162.2, 141.8, 124.7, 61.8, 31.1, 20.9, 14.0, 13.6.

Ethyl (2-chlorocyclohexylidene)acetate 11f.[25] (91% yield). ^{1}H NMR δ: 4.22 (2H, q, J=7.2 Hz), 2.59 (2H, m), 2.45 (2H, m), 1.58 (6H, m), 1.30 (3H, t, J=7.2 Hz), ^{13}C NMR δ: 162.5, 151.0, 125.0, 61.5, 32.6, 31.6, 27.6, 27.0, 25.8, 13.9.

α-Oxoesters 12

A solution of α-chloro-α-phenylselanyl ester **10** (1 mmol), mercuric acetate (0.382 g, 1.2 mmol) in a 1/1 mixture of acetone and water (5 ml) was stirred at room temperature for 1 h. After filtration, diethyl ether (5 ml) was added and the organic phase was washed with a 10% $NaHCO_3$ solution (4 ml), filtered, washed again three times with the same sodium bicarbonate solution (3 ml) and then with water. The organic layer was dried and concentrated. The crude produce was purified by Kugelrohr distillation.

Ethyl 2-oxobutanoate 12b.[26] (60% yield). ^{1}H NMR δ: 4.25 (2H, q, J=7.0 Hz), 2.81 (2H, q, J=7.1 Hz), 1.30 (3H, t, J=7.0 Hz), 1.06 (3H, t, J=7.1 Hz). ^{13}C NMR δ: 195.0, 160.8, 62.0, 32.5, 13.7, 6.7.

Ethyl 2-oxohexanoate 12d.[27] (67%) yield). ^{1}H NMR δ: 4.29 (2H, q, J=7.1 Hz), 2.80 (2H, t, J=7.2 Hz), 1.60 (2H, m), 1.34 (5H, m), 0.90 (3H, t, J=7.2 Hz). ^{13}C NMR δ: 194.5, 161.0, 62.1, 38.7, 24.7, 21.8, 13.7, 13.5.

Ethyl 3-methyl-2-oxobutanoate 12e. (66% yield). Commercial compound. ^{1}H NMR δ: 427 (2H, q, J=7.2 Hz), 3.20 (1H, m), 1.31 (3H, t, J=7.2 Hz), 1.10 (6H, d, J=7.0 Hz). ^{13}C NMR δ: 197.8, 161.5, 61.8, 36.6, 13.7, 11.3.

Ethyl cyclohexyloxoacetate 12f.[8] (66% yield). ^{1}H NMR δ: 426 (2H, q, J=7.2 Hz), 2.98 (1H, m), 1.50–1.92 (6H, m), 1.15–1.40 (7H, m). ^{13}C NMR ($CDCl_3$) δ: 197.1, 161.7, 62.0, 46.1, 27.3, 25.5, 25.1, 13.9.

α,α-Dimethoxy esters 13

A mixture of α-chloro-α-phenylselanylester **10** (1 mmol), mercuric acetate (0.382 g, 1.2 mmol) in methanol (5 ml) was stirred at room temperature for 24 h. After evaporation of the solvent, addition of water, the product was extracted with ether (3×5 ml). The organic solution was then treated as above. The purification was achieved by Kugelrohr distillation.

Ethyl 2,2-dimethoxybutanoate 13b. (48% yield). ^{1}H NMR δ: 4.22 (2H, q, J=7.1 Hz), 3.19 (6H, s), 1.83 (2H, q, J=7.5 Hz), 1.26 (3H, t, J=7.1 Hz), 0.76 (3H, t, J=7.5 Hz). ^{13}C NMR δ: 168.9, 102.9, 61.4, 49.5, 26.3, 14.1, 7.3. IR (cm^{-1}): 1743. Anal. Calcd for $C_8H_{16}O_4$: C, 54.53. H, 9.15. Found: C, 54.60. H, 9.09.

Ethyl 2,2-dimethoxyhexanoate 13d. (65% yield). ^{1}H NMR δ: 4.26 (2H, q, J=7.1 Hz), 3.23 (6H, s), 1.85 (2H, m), 1.30 (3H, t, J=7.1 Hz), 1.10–1.35 (4H, m), 0.86 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 168.9, 102.8, 61.3, 49.4, 33.1, 25.1, 22.4, 14.1, 13.6. IR (cm^{-1}): 1753. Anal. Calcd for $C_{10}H_{20}O_4$: C, 58.80; H, 9.87. Found: C, 59.13; H, 9.98.

Ethyl 2,2-dimethoxy-3-methylbutanoate 13e. (50% yield). ^{1}H NMR δ: 4.25 (2H, q, J=7.1 Hz), 3.23 (6H, s), 2.18 (1H, m), 1.28 (3H, t, J=7.1 Hz), 0.92 (6H, d, J=7.0 Hz). ^{13}C NMR δ: 168.2, 104.2, 61.2, 49.7, 31.8, 16.8, 14.3. IR (cm^{-1}): 1743. Anal. Calcd for $C_9H_{18}O_4$: C, 56.81; H, 9.54. Found: C, 57.11; H, 9.61.

Ethyl cyclohexyl(dimethoxy)acetate 13f. (64% yield). ^{1}H NMR δ: 4.22 (2H, q, J=7.1 Hz), 3.20 (6H, s), 1.50–1.90 (7H, m), 1.27 (3H, t, J=7.1 Hz), 0.80–1.30 (4H, m). ^{13}C NMR δ: 168.0, 104.2, 61.1, 49.6, 41.8, 27.0, 26.2, 26.1, 14.2. IR (cm^{-1}): 1743. Anal. Calcd for $C_{12}H_{22}O_4$: C, 62.58; H, 9.63. Found: C, 62.41; H, 9.59.

α-Bromo-α-chloroesters 14

N-Bromosuccinimide (0.235 g, 1.2 mmol) was added very slowly to a solution of α-chloro-α-phenylselanyl ester **10** (1 mmol) in CCl_4 (15 ml) at reflux. The mixture was heated for 2.5 h, then cooled to −20°C, filtered on celite and rinsed twice with the same solvent (2×5 ml). The organic solution was evaporated and the oily residue was rectified by Kugelrohr distillation to eliminate the corresponding unsaturated α-chloroester **11** always formed besides the expected α-bromo-α-chloroester **14**. The residual oil was then quickly chromatographed on silica gel (elution light petroleum/ethyl acetate: 90/10).

Ethyl 2-bromo-2-chlorobutanoate 14b. (44% yield). ^{1}H NMR δ: 4.31 (2H, q, J=7.0 Hz), 2.51 (2H, q, J=7.0 Hz), 1.33 (3H, t, J=7.0 Hz), 1.14 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 166.3, 74.3, 63.6, 39.5, 13.7, 10.6. IR (cm^{-1}): 1740. Anal. Calcd for $C_6H_{10}O_2BrCl$: C, 31.40; H, 4.39. Found: C, 31.27; H, 4.29.

Ethyl 2-bromo-2-chlorohexanoate 14d.[16] (33% yield). ^{1}H NMR δ: 4.32 (2H, q, J=7.0 Hz), 2.46 (2H, q, J=7.0 Hz), 1.70–1.20 (7H, m), 0.90 (3H, t, J=7.0 Hz). MS: (M^+−56): 200, 202, 204. ^{13}C NMR δ: 166.2, 73.2, 63.6, 45.79, 28.2, 21.9, 13.7. IR (cm^{-1}): 1756, 1740. Anal. Calcd for $C_8H_{14}O_2BrCl$: C, 37.30; H, 5.48. Found: C, 37.12; H, 5.37.

Ethyl 2-bromo-2-chloro-3-methylbutanoate 14e. (51% yield). ^{1}H NMR δ: 4.32 (2H, q, J=7.0 Hz), 2.73 (2H, q, J=7.0 Hz), 1.33 (3H, t, J=7.0 Hz), 1.22 (3H, d, J=7.0 Hz), 1.03 (3H, d, J=7.0 Hz). ^{13}C NMR δ: 166.2, 81.1, 63.6, 40.8, 18.6, 17.9, 13.7. IR (cm^{-1}): 1755, 1739. MS: (M^+−42): 200, 202, 204. Anal. Calcd for $C_7H_{12}O_2BrCl$: C, 34.52; H, 4.97. Found: C, 34.74; H, 5.04.

α-Chloroester 16a and β-chloroesters 5

The α,β-unsaturated esters **15a**–**15d** were subjected to the addition of PhSeCl in the presence of $ZnCl_2$.[2] The preparation of the β-chloro-α-phenylselanyl esters **5b**, **5c** and **5d** was described in the preceding paper.[1] Ethyl acrylate **15a** has lead to a 1/1 mixture of chloroesters **16a** and **5a** (96%

yield), separated by silica gel chromatography (elution: light petroleum/CH_2Cl_2: 70/30).

Ethyl 2-chloro-3-phenylselanylpropanoate 16a. (38% yield) ^{1}H NMR δ: 7.50–7.56 (2H, m), 7.23–7.37 (3H, m), 4.30 (1H, m), 4.16 (2H, q, J=7.0 Hz), 3.17–3.42 (2H, m), 1.27 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 167.2, 133.9, 129.2, 128.0, 126.2, 62.1, 54.7, 30.4, 13.9.

Ethyl 3-chloro-2-phenylselanylpropanoate 5a. (40% yield) ^{1}H NMR δ: 7.56–7.62 (2H, m), 7.22–7.36 (3H, m), 4.20 (1H, d, J=7.2 Hz), 4.13 (1H, d, J=7.2 Hz), 3.72–3.92 (3H, m), 1.23 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 170.0, 136.0, 129.2, 126.1, 61.5, 43.7, 43.4, 13.9.

Ethyl 2,3-dichloro-3-phenylpropanoate 17[24]

Ethyl cinnamate (0.176 g, 1 mmol) was added to PhSeCl (0.384 g, 2 mmol) and $ZnCl_2$ (0.137 g, 1 mmol) in benzene (10 ml). The mixture was heated on reflux for 17 h, washed three times with water, dried and evaporated under reduced pressure. The oily residue was purified by silica gel chromatography (elution: light petroleum/CH_2Cl_2: 70/30). Compound **17** was obtained in 65% yield (63/37 erythro/threo mixture of diastereoisomers).

Erythro: ^{1}H NMR, δ: 7.37 (5H, m), 5.16 (1H, d, J=10.7 Hz), 4.58 (1H, d, J=10.7 Hz), 4.33 (2H, q, J=7.1 Hz), 1.35 (35, t, J=7.1 Hz). ^{13}C NMR, δ: 167.2, 136.2, 128.5, 127.9, 126.6, 62.2, 60.9, 58.8, 13.7.

Threo: ^{1}H NMR, δ 7.37 (5H, m), 5.27 (1H, d, J=8.6 Hz), 4.63 (1H, d, J=8.6 Hz), 4.03 (2H, q, J=7.1 Hz), 1.05 (3H, t, J=7.1 Hz). ^{13}C NMR, δ: 166.3, 136.4, 129.2, 128.5, 127.9, 63.4, 62.4, 60.9, 13.5.

Reaction of ethyl cyclohexylideneacetate with PhSeCl

Ethyl cyclohexylideneacetate **15f** (0.168 g, 1 mmol) dissolved in CH_2Cl_2 (10 ml) containing $ZnCl_2$ (0.137 g, 1 mmol) was treated with PhSeCl (0.384 g, 2 mmol). The mixture was stirred at room temperature for 10 h. The solution was washed with water (3×10 ml), dried, evaporated under reduced pressure. The oily residue was purified by silica gel chromatography (elution: light petroleum/CH_2Cl_2: 70/30). The chloroester **20** was isolated as an oil. The stereochemistry was not assigned.

Ethyl (2-chlorocyclohexylidene)acetate 20. (51% yield). ^{1}H NMR δ: 5.87 (1H, s), 4.52 (1H, m), 4.13 (2H, q, J=7.2 Hz), 3.01–3.15 (1H, m), 2.74–2.90 (1H, m), 1.35–2.10 (6H, m), 1.25 (3H, t, J=7.2 Hz). ^{13}C NMR δ: 165.1, 157.5, 114.6, 62.8, 59.2, 36.7, 26.3, 25.1, 21.2, 16.2 IR (cm^{-1}): 1718, 1609. MS: M^+=202–204. Anal. Calcd for $C_{10}H_{15}O_2Cl$: C, 59.25; H, 7.46. Found: C, 58.96; H, 7.62.

α,β-Dichloro-α-phenylselanyl esters 22

Method A: Decomposition of dichloro-adducts derived from esters **4**. Sulfuryl chloride (0.135 g, 1 mmol) was added to ester **4** (1 mmol) dissolved in cold hexane and the mixture was stirred for 15 min at −40°C. The solvent was evaporated and the residue was stirred for 3 h in chloroform. After concentration, the crude product was purified as above.

Method B: Chlorination of β-chloro-α-phenylselanyl esters **5**. A solution of *N*-chlorosuccinimide (0.137 g, 1 mmol) and ester **17** (1 mmol) in CCl_4 (15 ml) was heated at reflux for 2 h under stirring. After cooling, the mixture was filtered on celite, then rinsed with the same solvent (3×5 ml). The organic solution was dried and evaporated under reduced pressure. The oily residue was chromatographed on silica gel with chloroform as eluent.

Ethyl 2,3-dichloro-2-phenylselanylpropanoate 22a. (51% yield, method B). ^{1}H NMR δ: 7.65–7.70 (2H, m), 7.30–7.45 (3H, m), 4.16 (2H, m), 4.11 (1H, J=11.5 Hz), 3.97 (1H, d, J=11.5 Hz), 1.21 (3H, t, J=7.0 Hz). ^{13}C NMR δ: 166.1, 137.8, 130.4, 129.1, 125.8, 67.2, 63.1, 50.6, 13.6. MS: M^+=326. Anal. Calcd for $C_{11}H_{12}O_2Cl_2Se$: C, 40.51; H, 3.71. Found: C, 40.58; H, 3.88.

Ethyl 2,3-dichloro-2-phenylselanylbutanoate 22b. (94% yield, method A, 46/54 diast. ratio; 78% yield, method B, 40/60 diast. ratio). ^{1}H NMR: A diast.: 7.67–7.72 (2H, m), 7.350–7.45 (3H, m), 4.83 (1H, q, J=6.4 Hz), 3.91 (2H, m), 1.56 (3H, d, J=6.4 Hz), 1.06 (3H, t, J=7.1 Hz). B diast.: 7.60–7.65 (2H, m), 7.30–7.45 (3H, m), 4.79 (1H, q, J=6.6 Hz), 4.02 (2H, m), 1.86 (3H, d, J=6.6 Hz), 1.11 (3H, t, J=7.0 Hz). ^{13}C NMR ($CDCl_3$) δ: A diast.: 165.9, 137.2, 130.2, 128.7, 126.5, 74.5, 62.5, 61.8, 21.1, 13.4. B diast.: 165.9, 137.2, 130.2, 128.9, 126.4, 74.5, 62.5, 60.4, 20.5, 13.4. Anal. Calcd for $C_{12}H_{14}O_2Cl_2Se$: C, 42.38; H, 4.15. Found: C, 42.07; H, 4.10.

Ethyl 2,3-dichloro-2-phenylselanylhexanoate 22d. (92% yield, method A, 60/40 diast. ratio; 45% yield, method B, 27/73 diast. ratio): ^{1}H NMR δ: A diast.: 7.64–7.73 (2H, m), 7.25–7.40 (3H, m), 4.70 (1H, dd, J=0.8, 9.0 Hz), 3.88 (2H, m), 1.30–2.10 (4H, m), 0.85–1.15 (6H, m). B diast.: 7.58–7.68 (2H, m), 7.30–7.45 (3H, m), 4.57 (1H, dd, J=1.0, 11 Hz), 4.00 (2H, m), 2.30 (1H, m), 1.30–2.10 (3H, m), 0.85–1.15 (6H, m). ^{13}C NMR δ: A and B diast. mixture: 166.0, 137.4, 130.2, 130.0, 128.9, 128.7, 74.9, 67.0, 65.9, 62.7, 36.8, 35.5, 19.6, 13.5, 13.2, 13.0. Anal. Calcd for $C_{14}H_{18}O_2Cl_2Se$: C, 45.67; H, 4.93. Found: C, 45.23; H, 4.87.

Ethyl chloro (1-chlorocyclohexyl) phenylselanylacetate 22f. (94% yield, method A). ^{1}H NMR δ: 7.65–7.70 (2H, m), 7.18–7.45 (3H, m), 4.01 (2H, m), 2.73 (1H, m), 2.48 (1H, m), 1.95–2.20 (2H, m), 1.60–1.85 (6H, m), 1.11 (3H, t, J=7.2 Hz). ^{13}C NMR δ: 166.9, 138.0, 130.0, 128.6, 82.7, 79.8, 62.7, 36.4, 36.3, 24.5, 22.2, 13.5. Anal. Calcd for $C_{16}H_{20}O_2Cl_2Se$: C, 48.75; H, 5.11. Found: C, 48.72; H, 5.08.

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