Use of *O,Se*-Acetals for Radical-Mediated Phenylseleno Group Transfer Reactions

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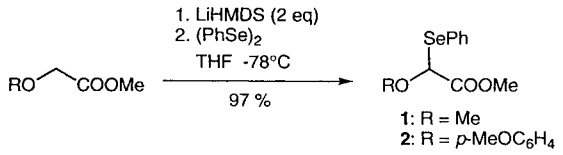
Received 1 August 1995; revised 25 September 1995

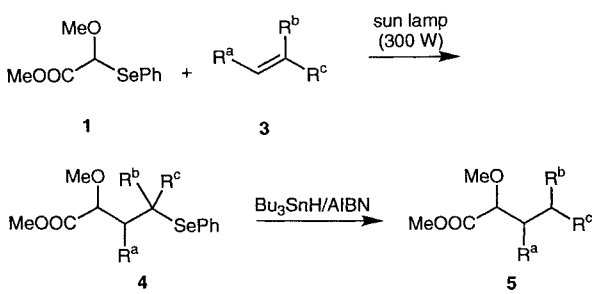
Ester substituted *O,Se*-acetals are very efficient radical precursors which can be used for intermolecular formation of C–C bonds via phenylseleno group transfer. The nucleophilic nature of the radical intermediates has been demonstrated and good yields were obtained with alkenes substituted by electron-withdrawing groups. Interestingly, the slow rate of phenylseleno group transfer permitted addition to nonactivated olefins. An intramolecular variant of this reaction provides a simple and efficient access to tetrahydrofuran derivatives.

Organoselenium compounds are highly versatile intermediates in organic synthesis.[1] For example, they can be converted to alkenes by oxidative elimination, to protected aldehydes by a seleno-Pummerer rearrangement[2] and to alkanes by reduction with Raney nickel or tin hydride. The homolytic cleavage of a C–Se bond has been widely used for the generation of radicals.[3] Recently, Byers has demonstrated the utility of this process in the intermolecular coupling of alkenes with dimethyl (phenylseleno)propanedioate with formation of new C–C bonds under phenylseleno group transfer conditions.[4] Interestingly, these transfer reactions are relatively slow and allow the rearrangement of the radical intermediate. We have recently exploited this feature in the synthesis of prostaglandin derivatives.[5] We now report that *O,Se*-acetals, obtained by selanylation of alkoxyacetates, are suitable precursors for inter- and intramolecular formation of C–C bonds via radical-mediated transfer of a phenylseleno group.[6,7]

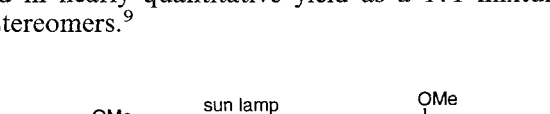
The radical precursor **1** was prepared in 97% yield from commercially available methyl methoxyacetate by selanylation with LiHMDS/$(PhSe)_2$ at −78 °C. The product, which is purified by flash chromatography, can be stored in the freezer for several weeks.



Reaction of this reagent with various olefins **(3a–3h)** was investigated and the results are summarized in the Table.



The reaction proceeds within a few hours upon irradiation (sun lamp 300 W) of a 0.33 M solution of the olefin in benzene with 1.5 equivalent of **1**. The use of the radical initiator AIBN was not necessary and is to be avoided as the addition of the 2-(cyano)prop-2-yl radical to the olefins occurs. The reaction is particularly efficient with olefins substituted with electron-withdrawing groups (entries **3a–3e**).[8] Electron-rich olefins, such as ethyl vinyl ether **(3f)**, gave no addition products. Modest yields were obtained with unactivated alkenes such as octene **(3g)**, even when large excesses were used (10 mmol). Interestingly, dihydronaphthalene epoxide **3h** gaves the addition product **5h** in 61% overall yield after reductive deselanylation of the intermediate **4h**. In every trial, the dimer **6** and diphenyl diselenide were observed. This dimerization is particularly efficient in the absence of olefin whereby dimethyl 2,3-dimethoxysuccinate **(6)** can be isolated in nearly quantitative yield as a 1:1 mixture of diastereomers.[9]



From a synthetic point of view, it would be attractive to prepare unprotected α-hydroxy acids or esters by this procedure. Preliminary experiments have demonstrated that the removal of the methyl ether protective group using BBr_3/CH_2Cl_2 is inefficient. To overcome this, we prepared the radical precursor **2** in which the alcohol is protected as its *p*-methoxyphenyl (PMP) ether. The radical addition of **2** to phenyl vinyl sulfone **(3c)** gave **7** which was reduced with Bu_3SnH to afford **8** (42% overall yield). Deprotection of **8** with cerium(IV) ammonium nitrate (CAN) in acetonitrile gave the α-hydroxy ester **9** in 73% yield.

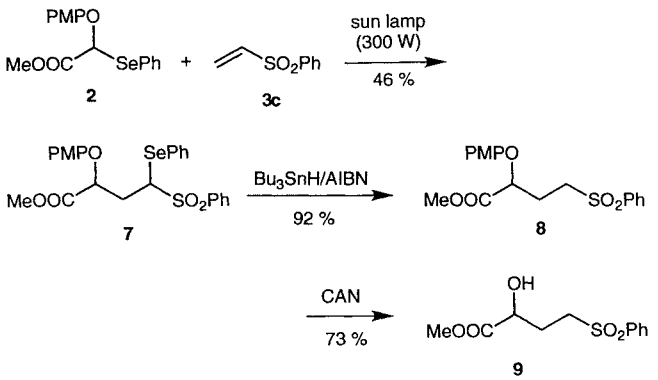
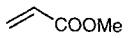
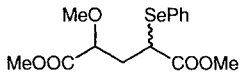
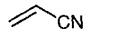
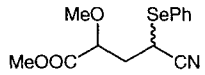
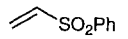
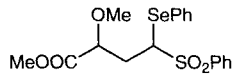
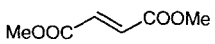
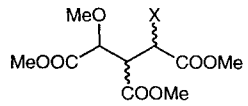
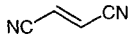
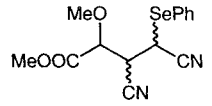
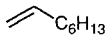
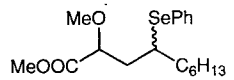
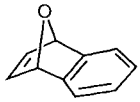
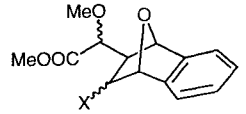
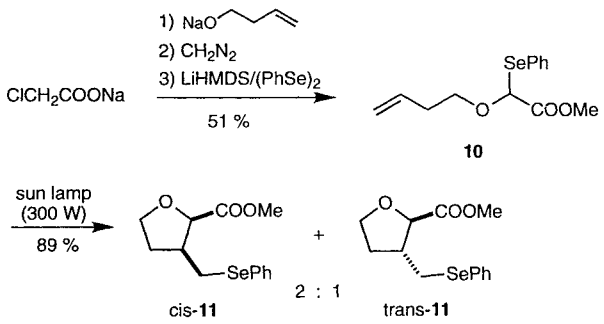


Table. Radical Addition of **1** to Olefins **3**

Olefin		Product		Yield (%)[a]
3a		**4a**		51
3b		**4b**		64
3c		**4c**		87
3d		**4d** (X = SePh) **5d** (X = H)		87[b]
3e		**4e** (X = SePh) **5e** (X = H)		92
3f		**4f**	–	–
3g		**4g**		52[c]
3h		**4h** (X = SePh) **5h** (X = H)		61[b]

[a] A solution of **1** (1.5 mmol) and the olefin (1.0 mmol) in benzene was irradiated with a sun lamp (300 W) for 5 h at 40 °C.
[b] The product was reduced (Bu_3SnH/AIBN) to enable characterization, overall yield is reported.
[c] A solution of octene (10 mmol), **1** (1.0 mmol) and AIBN in benzene was heated under reflux for 48 h.

Finally, the preparation of tetrahydrofuran derivatives by an intramolecular version of the reaction was investigated.[10] The radical precursor **10** was prepared from sodium chloroacetate in three steps. Reaction of the former with but-3-en-1-ol/NaH followed by esterification with diazomethane and selanylation [LiHMDS/$(PhSe)_2$] furnished the desired phenylseleno ester **10** in 51 % overall yield. Irradiation of **10** at 10 °C for 8 h gave the disubstituted furan **11** in 89 % yield as a 2:1 *cis*/*trans* mixture. The relative configuration of the two products was determined by NOE measurements.



In conclusion, we have demonstrated that inter- and intramolecular formation of C–C bonds via transfer of the phenylseleno radical is an effective method for the preparation of α-alkoxy and α-hydroxy acids derivatives. The synthetic versatility of the phenylseleno group renders this strategy particularly attractive. Moreover, through the use of a chiral auxiliary, this methodology should permit the preparation of optically active compounds. This possibility is currently under investigation in our laboratory.

Irradiations were performed using a sun lamp Osram Ultra-Vitalux 300 W. IR: Perkin-Elmer 16PC. FT-IR: Mattson Unicam 5000. NMR: Bruker AM 360 (^1H = 360 MHz ^{13}C = 90.5 MHz) and Varian Gemini 200 (^1H = 200 MHz, ^{13}C = 50.3 MHz); chemical shift in ppm relative to TMS. MS: Vacuum Generators Micromass VG 70/70 E and DS 11-250; Cl (NH_3), EI (70 eV); *m/z* (%). Elemental analysis: Ilse Beetz, Microanalytisches Laboratorium, D-8640 Kronach, Germany and Ciba-Geigy, Microlabor, CH-1700, Fribourg-Marly, Switzerland.

Methyl Methoxy(phenylseleno)acetate (1):
0.7 M LiHMDS in THF (57.2 mL, 40 mmol) was added to methyl methoxyacetate (1.98 mL, 20 mmol) in THF (40 mL) at −78 °C. After stirring for 10 min, a solution of $(PhSe)_2$ (6.24 g, 20 mmol) in THF (20 mL) was added dropwise. The reaction mixture was allowed to warm to −60 °C over 1 h and poured into 10% NH_4Cl and extracted with Et_2O. The organic phase was washed with 10% NH_4Cl, brine and dried ($MgSO_4$). After evaporation of the solvent, FC (EtOAc/hexane, 1:5) of the crude product gave **1**; yield: 5.03 g (97%).

^1H NMR (200 MHz, $CDCl_3$): δ = 7.57 (m, 2 arom H), 7.28 (m, 3 arom H), 5.35 (s, CH−Se), 3.61 (s, $COOCH_3$), 3.49 (s, OCH_3).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 168.3 (s), 135.6 (d), 128.8 (d), 128.4 (d), 126.9 (s), 82.7 (d), 56.7 (q), 51.9 (q).

IR (film): ν = 2999, 1950, 2829, 1750, 1578, 1476, 1437, 1276, 1235, 1194, 1153, 1096, 1021, 741 cm^{-1}.

EI-MS: *m/z* (%) = 260 (8, $[M+1]^+$), 201 (2), 157 (17), 121 (13), 103 (49), 75 (100), 51 (14), 31 (31).

Anal. calc. for $C_{10}H_{12}O_3Se$ (259.16): C 46.35, H 4.67; found: C 46.63, H 4.73.

Methyl (4-Methoxyphenoxy)(phenylseleno)acetate **(2)**:
According to the procedure described for **1**. From methyl (4-methoxyphenoxy)acetate (3.68 g, 20 mmol), LiHMDS (51 mL, 40 mmol) and $(PhSe)_2$ (6.24 g, 20 mmol). FC (EtOAc/hexane, 1:5) of the crude mixture gave the product **2**; yield: 5.58 g (83%).

^1H NMR (200 MHz, $CDCl_3$): δ = 7.6 (m, 2 arom H), 7.37 (m, 3 arom H), 6.94 (m, 2 arom H), 6.84 (m, 2 arom H), 5.28 (s, CH−Se), 3.76 (s, $COOCH_3$), 3.68 (s, OCH_3).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 168.3 (s), 155.5 (s), 150.0 (s), 136.2 (d), 129.0 (d), 128.8 (d), 126.8 (s), 118.3 (d), 114.7 (d), 78.37 (d), 55.5 (q), 52.3 (q).

IR (film): ν = 3057, 3000, 2951, 2835, 1753, 1504, 1438, 1243, 1209, 1063, 826, 741 cm^{-1}.

CI-MS: *m/z* (%) = 331 (14), 260 (9), 229 (100), 197 (19), 132 (14), 103 (64).

Anal. calc. for $C_{16}H_{16}O_4Se$ (351.26): C 54.71, H 4.59; found: C 54.69, H 4.70.

General Procedure for Radical Additions:
A solution of **1** or **2** (3.0 mmol) and the olefin (2.0 mmol) in benzene (9 mL) was irradiated with a 300 W sun lamp for 5 h. The crude product was purified by FC.

Dimethyl 2-Methoxy-4-(phenylseleno)pentanedioate **(4a)**:
According to general procedure. From **1** (0.78 g, 3.0 mmol) and methyl acrylate (172 mg, 2.0 mmol) in benzene (9 mL). FC (EtOAc/hexane 1:5) of the crude product gave **4a**; yield: 350 mg (51%); 1:1 mixture of diastereomers.

^1H NMR (200 MHz, $CDCl_3$): δ = 7.56 (m, 2 arom H), 7.29 (m, 3 arom H), 4.05 [dd, *J* = 4.3, 9.0 Hz, CH−O (one diast.)], 3.82 [m, CH−O (one diast.) and CH−Se], 3.73, 3.72, 3.66 and 3.65 (4s, $COOCH_3$), 3.33 and 3.32 (2s, OCH_3), 2.25 (m, CH_2).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 173.2 (s), 173.0 (s), 172.7 (s), 172.4 (s), 136.1 (d), 129.5 (d), 129.1 (d), 127.9 (s), 127.7 (s), 78.9 (d), 78.6 (d), 58.7 (q), 52.5 (d), 52.3 (d), 40.3 (q), 39.1 (q), 35.8 (t), 35.2 (t).

IR (film): ν = 2996, 2952, 2832, 1751, 1731, 1578, 1437, 1261, 1203, 1180, 1165, 1127, 1047 cm^{-1}.

EI-MS: *m/z* (%) = 346 (10, $[M+1]^+$), 345 (1, M^+), 314 (7), 255 (5), 195 (8), 189 (35), 157 (76), 129 (100), 101 (25), 77 (16), 75 (26).

Anal. calc. for $C_{14}H_{18}O_5Se$ (345.26): C 48.7, H 5.26; found: C 49.0, H 5.15.

Methyl 4-Cyano-2-methoxy-4-(phenylseleno)butyrate **(4b)**:
According to general procedure. From **1** (0.78 g, 3 mmol) and acrylonitrile (106 mg, 2 mmol). FC (EtOAc/hexane 1:3) of the crude mixture gave **4b**; yield: 400 mg (64%); mixture of 2 diastereomers which were separated by recrystallization (Et_2O/hexane, 2:1).

Diastereomer 1:
^1H NMR (200 MHz, $CDCl_3$): δ = 7.74 (m, 2 arom H), 7.41 (m, 3 arom H), 3.9 (m, CH−O, CH−Se), 3.76 (s, $COOCH_3$), 3.44 (s, OCH_3), 2.18–2.16 (m, CH_2).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 171.9 (s), 136.8 (d), 130.3 (d), 126.9 (s), 119.9 (s), 78.2 (d), 59.1 (d), 52.6 (q), 39.9 (q), 22.7 (t).

Diastereomer 2:
^1H NMR (200 MHz, $CDCl_3$): δ = 7.73 (m, 2 arom H), 7.38 (m, 3 arom H), 4.11 (dd, *J* = 4.25, 9.0 Hz, CH−O), 3.87 (dd, *J* = 5.8, 9.4 Hz, CH−Se), 3.77 (s, $COOCH_3$), 3.43 (s, OCH_3), 2.25–2.1 (m, CH_2).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 171.7 (s), 136.9 (d), 130.4 (d), 125.9 (s), 119.5 (s), 78.5 (d), 59.2 (d), 52.6 (q), 36.9 (q), 22.0 (t).

Mixture of diastereomers:
IR (film): ν = 3006, 2950, 2932, 2895, 2869, 2360, 1748, 1705, 1475, 1431, 1280, 1207, 1186, 1126, 736, 689 cm^{-1}.

EI-MS: *m/z* (%) = 313 (29, $[M+1]^+$), 312 (8, M^+), 254 (8), 222 (9), 195 (7), 169 (7), 156 (57), 117 (32), 104 (100), 75 (66), 51 (24).

Anal. calc. for $C_{13}H_{15}NO_3Se$ (312.22): C 50.01, H 4.84, N 4.49; found: C 50.00, H 4.88, N 4.35.

Methyl 2-Methoxy-4-(phenylseleno)-4-phenylsulfonylbutyrate **(4c)**:
According to general procedure. From **1** (1.04 g, 4 mmol) and phenyl vinyl sulfone (336 mg, 2.0 mmol). FC (EtOAc/hexane, 1:3) of the crude product gave **4c**; yield: 0.744 g (87%); 1:1 mixture of diastereomers.

^1H NMR (200 MHz, $CDCl_3$): δ = 7.87 (m, 2 arom H), 7.5 (m, 5 arom H), 7.22 (m, 3 arom H), 4.44 [dd, *J* = 5.3, 8.7 Hz, CH−Se (one diast.)], 4.40 [dd, *J* = 2.9, 12.3 Hz, CH−Se (one diast.)], 4.27 (dd, *J* = 2.7, 11.0 Hz, CH−O (one diast.)], 4.15 [t, *J* = 6.0 Hz, CH−O (one diast.)], 3.74 (s) and 3.7 (2 s, $COOCH_3$), 3.38 and 3.27 (2 s, OCH_3), 2.75–2.06 (m, CH_2).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 172.3 (s), 170 (s), 137 (s), 135.4 (d), 135.2 (d), 134.4 (d), 134.2 (d), 139.9 (d), 129.7 (d), 77.9 (d), 77.6 (d), 65.4 (d), 62.3 (d), 58.8 (q), 58.6 (q), 52.6 (q), 52.4 (q), 33.2 (t), 32.7 (t).

IR (film): ν = 2984, 2954, 2937, 1754, 1736, 1731, 1578, 1446, 1438, 1255, 1207, 1151, 743, 692 cm^{-1}.

EI-MS: *m/z* (%) = 428 (4, $[M+1]^+$), 287 (17), 255 (100), 227 (35), 195 (38), 157 (11), 125 (5), 115 (5), 77 (45), 51 (25).

Anal. calc. for $C_{18}H_{20}O_5SSe$ (427.37): C 50.59, H 4.72; found: C 50.60, H 4.77.

Dimethyl 2-Methoxy-3-(methoxycarbonyl)pentane-1,5-dioate **(5d)**:
According to general procedure. From **1** (0.78 g, 3 mmol) and dimethyl fumarate (0.288 g, 2 mmol). FC (EtOAc/hexane, 1:4) of the crude mixture gave **4d**; yield (%): 0.71 g (88%); mixture of 4 diastereomers. For characterization, a solution of **4d** (0.71 g, 1.75 mmol), Bu_3SnH (0.594 g, 2 mmol) and AIBN in benzene (5 mL) was irradiated with a 300 W sun lamp for 2 h to give **5d** as a mixture of 2 diastereomers which can be separated by FC (EtOAc/hexane, 1:4).

Diastereomer 1:
^1H NMR (360 MHz, $CDCl_3$): δ = 4.25 (d, *J* = 4.6 Hz, CH−O), 3.77, 3.74 and 3.68 (3 s, $COOCH_3$), 3.53 (ddd, *J* = 4.6, 4.7, 8.8 Hz, C*H*CH_2), 3.40 (s, OCH_3), 2.89 (dd, *J* = 8.8, 17.1 Hz, C*H*H), 2.59 (dd, *J* = 4.7, 17.1 Hz, CH*H*).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 172.2 (s), 171.7 (s), 171 (s), 79.8 (d), 59 (q), 52.3 (q), 52.1 (q), 51.8 (q), 44.3 (d), 30.8 (t).

Diastereomer 2:

^{1}H NMR (360 MHz, $CDCl_3$): δ = 4.05 (d, J = 4.3 Hz, CH−O), 3.77, 3.71 and 3.69 (3 s, $COOCH_3$), 3.53 (ddd, J = 4.3, 5.3, 8.8 Hz, C*H*CH_2), 3.39 (s, OCH_3), 2.84 (dd, J = 8.85, 17.09 Hz, C*H*H), 2.59 (dd, J = 5.3, 17.1 Hz, CH*H*).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 171.4 (s), 171.3 (s), 170.9 (s), 80.3 (d), 59.4 (q), 52.5 (q), 52.4 (q), 52.2 (q), 44.3 (d), 32 (t).

Mixture of diastereomers:

IR (film): ν = 2999, 2838, 1741, 1438, 1367, 1347, 1272, 1210, 1167, 1137, 1005, 849 cm^{-1}.

CI-MS: m/z (%) = 249 (13, $[M + 1]^+$), 217 (19), 189 (100), 157 (30), 129 (2), 41 (1).

Anal. calc. for $C_{10}H_{16}O_7$ (248.23): C 48.39, H 6.50; found: C 48.47, H 6.53.

Methyl 3,4-Dicyano-2-methoxy-4-(phenylseleno)butyrate (**4e**):

According to general procedure. From **1** (0.78 g, 3 mmol) and fumaronitrile (156 mg, 2.0 mmol). FC (EtOAc/hexane, 1:4) gave **4e**; yield: 0.629 g (93%) as a mixture of 4 diastereomers. Recrystallization (Et_2O/hexane 2:1) gave a mixture of diast. 1 and 2. A mixture of the two other diastereomers was obtained by concentration of the mother liquor.

Diastereomer 1:

^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.75 (m, 2 arom H), 7.45 (m, 3 arom H), 4.13 (d, J = 5.1 Hz, CH−O), 4.05 (d, J = 8.8 Hz, CH−Se), 3.83 (s, $COOCH_3$), 3.59 (s, OCH_3), 3.38 (dd, J = 5.07, 8.83 Hz, CH−CN).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 168.3 (s), 137.1 (d), 130.7 (d), 129.9 (d), 124.3 (s), 116.4 (s), 115.3 (s), 77.9 (d), 60.1 (d), 52.8 (q), 39 (q), 22.8 (d).

Diastereomer 2:

^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.75 (m, 2 arom H), 7.45 (m, 3 arom H), 4.04 (d, J = 3.3 Hz, CH−O), 4.01 (d, J = 11.3 Hz, CH−Se), 3.81 (s, $COOCH_3$), 3.51 (s, OCH_3), 3.22 (dd, J = 3.3, 11.3 Hz, CH−CN).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 168.2 (s), 137.1 (d), 130.5 (d), 129.8 (d), 123.6 (s), 116.3 (s), 114.6 (s), 78.2 (d), 59.7 (d), 52.8 (q), 38.7 (q), 23.8 (d).

Diastereomer 3:

^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.75 (m, 2 arom H), 7.45 (m, 3 arom, H), 4.39 (d, J = 3.6 Hz, CH−O), 4.03 (d, J = 9.2 Hz, CH−Se), 3.85 (s, $COOCH_3$), 3.57 (s, OCH_3), 3.28 (dd, J = 3.6, 9.2 Hz, CH−CN).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 168.6 (s), 136.7 (d), 130.6 (d), 129.8 (d), 124.2 (s), 116.4 (s), 114.3 (s), 77.6 (d), 59.1 (d), 52.8 (q), 38.2 (q), 24.5 (d).

Diastereomer 4:

^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.75 (m, 2 arom H), 7.44 (m, 3 arom H), 4.13 (d, J = 5.3 Hz, CH−O), 4.12 (d, J = 7.6 Hz, CH−Se), 3.85 (s, $COOCH_3$), 3.52 (s, OCH_3), 3.38 (dd, J = 5.3, 7.6 Hz, CH−CN).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 168.4 (s), 136.3 (d), 130.3 (d), 129.9 (d), 125.2 (s), 115.9 (s), 114.6 (s), 78.4 (d), 59.6 (d), 52.8 (q), 38.7 (q), 23.4 (d).

Mixture of diastereomers:

IR (KBr): ν = 2995, 2955, 2936, 2839, 1765, 1749, 1440, 1236, 1225, 1133, 749, 738, 690 cm^{-1}.

EI-MS: m/z (%) = 338 (11, $[M + 1]^+$), 196 (9), 169 (13), 157 (65), 104 (100), 77 (53), 75 (56), 51 (25).

Anal. calc. for $C_{14}H_{14}O_3N_2Se$ (337.24): C 49.86, H 4.16; found: C 49.87, H 4.24.

Methyl 2-Methoxy-4-(phenylseleno)decanoate (4g):

A solution of octene (0.56 g, 5 mmol), **1** (258 mg, 1.0 mmol) and AIBN (4 mL, 0.05 M in benzene) in benzene (3 mL) was heated at reflux for 48 h. AIBN (0.5 mL, 0.2 M in benzene) was added every 6 h. Evaporation of the solvent and FC (EtOAc/hexane, 1:10) of the crude mixture gave **4g** (37 mg, 10%, 50% based on reacted **1**) as a 1:1 mixture of diastereomers and the starting precursor **1** (208 mg, 0.8 mmol).

^{1}H NMR (360 MHz, $CDCl_3$): δ = 7.55 (m, 2 arom H), 7.25 (m, 3 arom H), 4.22 [dd, J = 2.7, 10.4 Hz, CH−O (one diast.)], 3.98 [dd, J = 4.9, 8.0 Hz, CH−O (one diast.)], 3.73 and 3.72 (2 s, $COOCH_3$), 3.36 (m, CH−Se), 3.23 (s, OCH_3), 2.87 (m, CH_2), 1.55 (m, $2CH_2$), 1.25 (m, $3CH_2$), 0.87 (s, CH_3).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 173.8 (s), 173.3 (s), 135.6 (d), 129.5 (s), 129.3 (d), 127.9 (d), 79.4 (d), 58.6 (q), 58.5 (q), 52.2 (d), 43.7 (q), 42.9 (q), 40.0 (t), 39.3 (t), 37.2 (t), 37.1 (t), 32.1 (t), 29.4 (t), 28.1 (t), 27.8 (t), 22.9 (t), 14.4 (q).

IR (film): ν = 2953, 2927, 2856, 1753, 1738, 1579, 1437, 1300, 1268, 1199, 1180, 1129, 1022, 739, 692 cm^{-1}.

EI-MS: m/z (%) = 372 (16, $[M + 1]^+$), 255 (6), 183 (23), 155 (91), 123 (100), 103 (25), 81 (60), 41 (77).

Anal. calc. for $C_{18}H_{28}OSe$ (371.38): C 58.22, H 7.60; found: C 58.01, H 7.58.

Methyl 2-Methoxy-2-(1,2,3,4-tetrahydro-1,4-epoxynaphthalen-2-yl)acetate (**5h**):

According to general procedure. From **1** (1.17 g, 4.5 mmol) and 1,4-dihydro-1,4-epoxynaphthalene (432 mg, 3.0 mmol); irradiation for 8 h. FC (EtOAc/hexane 1:5) of the crude product gave a mixture of 4 diastereomers which were reduced with Bu_3SnH (0.872 g, 3 mmol) and AIBN to give **5h**; yield: 0.458 g (62%); mixture of two diastereomers (ratio 2:1) separable by FC (EtOAc/hexane, 1:4).

Diastereomer 1 (major):

^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.2 (m, 4 arom H), 5.46 [s, H−C(1)], 5.37 [d, J = 4.88 Hz, H−C (4)], 3.76 (d, J = 9.96 Hz, C*H*OCH_3), 3.75 (s, $COOCH_3$), 3.45 (s, OCH_3), 2.08 [ddd, J = 4.3, 8.2, 10.0 Hz,H−C(2)], 1.86 [ddd, J = 4.3, 4.9, 11.9 Hz, H_{exo}−C (3)], 1.47 [dd, J = 8.2, 11.9 Hz, H_{endo}−C (3)].

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 172.1 (s), 145.9 (s), 144.5 (s), 126.6 (d), 126.5 (d), 119.2 (d), 118.7 (d), 83.2 (d), 80 (d), 79 (d), 58.1 (q), 51.8 (d), 43.7 (q), 30 (t).

Diastereomer 2 (minor):

^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.2 (m, 4 arom H); 5.35 [d, J = 4.5 Hz, H−C (4)], 5.33 [s, H−C (1)], 3.82 [d, J = 7.07 Hz, $CHOCH_3$), 3.82 (s, $COOCH_3$), 3.41 (s, OCH_3), 2.1 (m, CH_2).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 172 (s), 146.1 (s), 144.7 (s), 126.6 (d), 126.5 (d), 119 (d), 118.8 (d), 82.8 (d), 79.8 (d), 78.9 (d), 58.1 (q), 51.9 (d), 43.7 (q), 30.6 (t).

Mixture of diastereomers:

IR (KBr): ν = 2996, 2958, 2829, 1747, 1737, 1460, 1281, 1202, 1163, 1115, 839, 757 cm^{-1}.

EI-MS: m/z (%) = 248 (0.6, M^+), 189 (3), 118 (100), 115 (15), 89 (23), 61 (13), 45 (8).

HRMS calc. for $C_{14}H_{16}O_4$ (248.1048); found: 248.1050.

Dimethyl 2,3-Dimethoxysuccinate (6):

A solution of **1** (518 mg, 2.0 mmol) in benzene (5 mL) was irradiated for 20 h with a 300 W sun lamp. After evaporation, FC (EtOAc/hexane 1:2) gave the product **6**; yield: 0.190 g (92%); 1:1 mixture of diastereomers.

Diastereomer 1:

^{1}H NMR (360 MHz, $CDCl_3$): δ = 4.10 (s, CH), 3.68 (s, $COOCH_3$), 3.33 (s, OCH_3).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 169.9 (s), 81.5 (d), 59.7 (q), 52.4 (q).

Diastereomer 2:

^{1}H NMR (360 MHz, $CDCl_3$): δ = 4.07 (s, CH), 3.66 (s, $COOCH_3$), 3.37 (s, OCH_3).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 169.6 (s), 81.7 (d), 59.9 (q), 52.4 (q).

Mixture of diastereomers:

IR (film): ν = 2997, 2955, 2836, 1759, 1438, 1353, 1277, 1198, 1114, 991, 939 cm^{-1}.

EI-MS: *m/s* (%) = 207 (1, $[M+1]^+$), 206 (3, M^+), 147 (30), 119 (98), 103 (100), 88 (85), 75 (98), 59 (98), 45 (96), 31 (77).

Anal. calc. for $C_8H_{14}O_6$ (206.19): C 46.60, H 6.84; found: C 46.48, H 6.82.

Methyl 2-(4-Methoxyphenoxy)-4-(phenylseleno)-4-phenylsulfonylbutyrate (**7**):

According to general procedure. From **2** (0.45 g, 1.3 mmol) and phenyl vinyl sulfone (168 mg, 1.0 mmol); irradiated for 5.5 h. FC of the crude mixture gave the product **7**; yield: 238 mg (46%); mixture of two diastereomers.

Diastereomer 1:

^{1}H NMR (360 MHz, $CDCl_3$): δ = 7.9 (m, 2 arom H), 7.55 (m, 3 arom H), 7.29 (m, 3 arom H), 6.95 (m, 6 arom H), 4.97 (t, J = 6.1 Hz, CH−O), 4.52 (dd, J = 6.1, 8.5 Hz, CH−Se), 3.75 (s, $COOCH_3$), 3.69 (s, OCH_3), 2.77 (dt, J = 6.1, 15.2 Hz, C*H*H), 2.45 (ddd, J = 6.1, 8.5, 15.2 Hz, CH*H*).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 171.6 (s), 155.7 (s), 151.9 (s), 137.6 (s), 135.5 (d), 134.4 (d), 129.8 (d), 128.1 (s), 118.3 (d), 117.5 (d), 115 (d), 80.3 (d), 75.9 (d), 65.5 (q), 56.1 (q).

Diastereomer 2:

^{1}H NMR (360 MHz, $CDCl_3$): δ = 7.9 (m, 2 arom H), 7.55 (m, 3 arom H), 7.29 (m, 3 arom H), 6.95 (m, 6 arom H), 5.19 (dd, J = 2.5, 11.0 Hz, CH−O), 4.44 (dd, J = 2.75, 12.5 Hz, CH−Se), 3.76 (s, $COOCH_3$), 3.73 (s, OCH_3), 2.66 (ddd, J = 2.75, 11.0, 14.3 Hz, C*H*H), 2.22 (ddd, J = 2.5, 12.5, 14.3 Hz, CH*H*).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 171.3 (s), 155.4 (s), 151.9 (s), 137.5 (s), 135.4 (d), 134.3 (d), 129.6 (d), 127.7 (s), 118.2 (d), 117 (d), 115 (d), 79.6 (d), 62.4 (q), 53 (q).

Mixture of diastereomers:

IR (film): ν = 3060, 3002, 2953, 2934, 1754, 1510, 1477, 1464, 1292, 1228, 1218, 1121, 1150, 1083, 742 cm^{-1}.

EI-MS: *m/z* (%) = 520 (4, $[M+1]^+$), 519 (0.7, M^+), 390 (4), 221 (43), 161 (100), 123 (28), 77 (28), 51 (10).

Anal. calc. for $C_{24}H_{24}O_6SSe$ (519.47): C 55.49, H 4.66; found: C 55.40, H 4.73.

Methyl 2-(4-Methoxyphenoxy)-4-phenylsulfonylbutyrate (8):

A solution of **7** (0.60 g, 1.16 mmol) and Bu_3SnH (0.60 g, 2.0 mmol) and AIBN in benzene (3 mL) was irradiated for 4 h. FC (EtOAc/hexane 1:3) of the crude mixture gave **8**; yield: 388 mg (92%).

^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.92 (m, 2 arom H), 7.6 (m, 3 arom H), 6.78 (s, 4 arom H), 4.67 (dd, J = 4.5, 7.75 Hz, CH−O), 3.75 (s, $COOCH_3$), 3.73 (s, OCH_3), 3.34 (m, CH_2−S), 2.35 (m, CH_2).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 170 (s), 155.1 (s), 139.2 (s), 129.5 (d), 128.2 (d), 116.9 (d), 114.9 (d), 112.4 (s), 75.6 (d), 55.7 (q), 52.5 (q), 52.1 (t), 26.3 (t).

IR (film): ν = 3002, 2954, 2934, 1754, 1509, 1447, 1307, 1225, 1216, 1144, 736, 689 cm^{-1}.

EI-MS: *m/z* (%) = 364 (7, M^+), 241 (100), 163 (16), 141 (36), 123 (42), 77.4 (62).

Anal. calc. for $C_{18}H_{20}O_6S$ (364.41): C 59.33, H 5.53; found: C 59.29, H 5.62.

Methyl 2-Hydroxy-4-phenylsulfonylbutyrate (9):

A solution of CAN (1.64 g, 3.0 mmol) in water (5 mL) was added at 0 °C to **8** (364 mg, 1.0 mmol) in CH_3CN (2 mL). The reaction mixture was allowed to warm to r.t. and poured into EtOAc/H_2O. The organic phase was washed with brine and dried ($MgSO_4$). Evaporation of the solvent and FC (EtOAc/hexane 1:2) of the crude product gave **9**; yield: 177 mg (73%).

^{1}H NMR (360 MHz, $CDCl_3$): δ = 7.9 (m, 2 arom H), 7.62 (m, 3 arom H), 4.26 (dt, J = 4.7, 7.9 Hz, CH−O), 3.78 (s, $COOCH_3$), 3.23 (m, CH_2−S), 3.0 (d, J = 4.9 Hz, OH), 2.28 (m, C*H*H), 2.01 (m, CH*H*).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 173 (s), 138.9 (s), 133.7 (d), 129.3 (d), 127.9 (d), 68.4 (q), 52.7 (q), 52.1 (t), 27.3 (t).

IR (film): ν = 3444, 3061, 2935, 1740, 1452, 1343, 1309, 1266, 796, 690, 589, 531 cm^{-1}.

EI-MS: *m/z* (%) = 259 (1, $[M+1]^+$), 199 (27), 170 (12), 143 (100), 125 (51), 77 (97), 57 (84), 33 (52).

Anal. calc. for $C_{11}H_{14}O_5S$ (158.29): C 51.15, H 5.46; found: C 51.16, H 5.55.

Methyl 2-(But-3-enyloxy)-2-(phenylseleno)acetate (10):

But-3-en-1-ol (3.6 g, 50 mmol) was added by portion to a suspension of NaH (55% in oil, 2.2 g, 50 mmol) in THF (150 mL) followed by sodium chloroacetate (8.7 g, 80 mmol). The reaction mixture was heated under reflux for 24 h and treated with H_2O (80 mL). The aqueous phase was washed with Et_2O, acidified with 3 M HCl and extracted with CH_2Cl_2. Evaporation of the solvent gave the crude (but-3-enyloxy)acetic acid which was dissolved in Et_2O (50 mL) and esterified with diazomethane. Purification by FC gave methyl (but-3-enyloxy)acetate (3.98 g, 55%). This product was selanylated according to the procedure described for **1**. From methyl (but-3-enyloxy)acetate (1.44 g, 10 mmol), FC (EtOAc/hexane 1:10) of the crude mixture gave **10**; yield: 2.75 g (92%).

^{1}H NMR (200 MHz, $CDCl_3$): δ = 7.6 (m, 2 arom H), 7.28 (m, 3 arom H), 5.76 (m, CH=C), 5.45 (s, CH−Se), 5.07 (m, CH_2=C), 3.95 (dt, J = 6.9, 9.3 Hz, C*H*H−O), 3.63 (s, $COOCH_3$), 3.51 (dt, J = 6.9, 9.3 Hz, CH*H*−O), 2.39 (tq, J = 1.2, 6.9 Hz, CH_2).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 168.5 (s), 135.5 (d), 134.1 (d), 128.8 (d), 128.3 (d), 116.7 (t), 81.1 (d), 68.9 (t), 51.9 (q), 33.2 (t).

IR (film): ν = 3073, 2979, 2950, 2922, 1752, 1476, 1438, 1155, 1098, 1070, 740 cm^{-1}.

CI-MS: *m/z* (%) = 300.1 (2, $[M+1]^+$), 299.2 (2), 2315 (5), 229 (27), 197 (8), 143 (100), 115 (39), 83 (84), 55 (66), 41 (21).

Anal. calc. for $C_{13}H_{16}O_3Se$ (299.23): C 52.18, H 5.39; found: C 52.17, H 5.33.

Methyl 3-(Phenylselenomethyl)tetrahydrofuran-2-carboxylate (11):

A solution of **10** (299 mg, 1.0 mmol) in benzene (3 mL) was irradiated for 8 h. FC (EtOAc/hexane 1:10) of the crude product gave **11**; yield: 2.66 g (89%); *cis*/*trans* (2:1) mixture of isomers.

cis-**11**:

^{1}H NMR (360 MHz, $CDCl_3$): δ = 7.49 (m, 2 arom H), 7.35 (m, 3 arom H), 4.5 (d, J = 7.0 Hz, CH−O), 4.18 (dt, J = 4.3, 8.2 Hz, C*H*H−O), 3.88 (q, J = 8.2 Hz, 1 H, CH*H*−O), 3.75 (s, $COOCH_3$), 3.07 (dd, J = 4.6, 11.9 Hz, C*H*H−Se), 2.77 (m, CH*H*−Se, CH), 2.19 (m, C*H*H), 1.9 (dq, J = 8.24, 12.1, CH*H*).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 171.5 (s), 132.5 (d), 129.1 (d), 127.1 (d), 79.8 (d), 68.2 (t), 51.6 (q), 43.2 (d), 31.4 (t), 27.4 (t).

trans-**11**:

^{1}H NMR (360 MHz, $CDCl_3$): δ = 7.52 (m, 2 arom H), 7.28 (m, 3 arom H), 4.28 (d, J = 5.5 Hz, CH−O), 4.01 (m, CH_2−O), 3.73 (s, $COOCH_3$), 3.2 (dd, J = 6.1, 12.2 Hz, C*H*H−Se), 2.97 (dd, J = 8.5, 12.2 Hz, CH*H*−Se), 2.61 (m, CH), 2.19 (m, C*H*H), 1.77 (m, CH*H*).

^{13}C NMR (50.3 MHz, $CDCl_3$): δ = 173.3 (s), 135.2 (d), 133.4 (d), 130.1 (s), 129.6 (d), 127.6 (d), 82.1 (d), 69.1 (t), 52.4 (q), 45.1 (d), 32.8 (t), 31.8 (t).

Mixture of cis- and trans-**11**:

IR (film): ν = 2890, 2855, 1579, 1263, 1178, 1040 cm^{-1}.

CI-MS: *m/z* (%) = 300.1 (10, $[M+1]^+$), 299.1 (14) (M^+), 269 (9), 241 (100), 163 (34), 143 (63), 118 (25), 107 (16), 41 (27).

Anal. calc. for $C_{13}H_{16}O_3Se$ (299.23): C 52.18, H 5.39; found: C 52.26, H 5.41.

We are very grateful to the Swiss National Science Foundation for funding, to Ciba-Geigy AG (Marly) for performing the microanalysis and to Christoph Imboden for preliminary experiments.

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