A New, Simple, and Selective Palladium-Catalyzed Cleavage of Triethylsilyl Ethers (TES)

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General

¹H NMR spectra were recorded on a BRUKER AM 400 (400 MHz) instrument. The chemical shifts are expressed in parts per million (ppm) referenced to TMS (0 ppm). Data are reported as follows: δ , chemical shift; multiplicity (recorded as br, broad; s, singlet; d, doublet; t, triplet; q, quadruplet; quint, quintuplet; hex, hexuplet; hept, heptuplet; oct, octuplet and m, multiplet), coupling constants (J in Hertz, Hz), and integration.

¹³C NMR spectra were recorded on the same instrument at 100 MHz. The chemical shifts are expressed in parts per million (ppm), reported from the central peak of deuteriochloroform (77.14 ppm).

Infrared spectra (IR) were obtained on a PERKIN-ELMER FT 1600 instrument using NaCl salt plates (thin film) and are reported in terms of frequency of absorption (ν , cm⁻¹).

Mass spectra (MS) were obtained on a HEWLETT-PACKARD HP 5989B spectrometer *via* either direct introduction or GC/MS coupling with a HEWLETT-PACKARD HP 5890 chromatograph. Ionization was obtained by chemical ionisation with ammonia (IC, NH₃). Mass spectral data are reported as m/z .

Flash chromatography was performed on silica gel 60, 230-400 mesh.

Microanalyses were performed by the Service de Microanalyse, Institut de Chimie des Substances Naturelles, C.N.R.S., F-91198, Gif sur Yvette.

Procedures for protection of hydroxy functional groups as triethylsilyl ethers:

- Procedure A: with TESCl

To a solution of alcohol in dichloromethane at room temperature was added 1.2-1.3 equiv of triethylamine and 0.2 equiv of DMAP followed by 1.1-1.2 equiv of triethylsilyl chloride. The resulting mixture was stirred at room temperature until completion of the reaction. Methanol was then added to quench the excess of triethylsilyl chloride, and after 30 min a saturated aqueous NH₄Cl solution was added. The aqueous layer was separated, extracted 3 times with ether and the combined organic phases were washed with brine, dried over anhydrous MgSO₄, filtered and concentrated *in vacuo*. The crude residue was then purified by flash chromatography on silica gel.

- Procedure B: with TESOTf

To a solution of alcohol in dichloromethane at -78°C was added 1.2-2.1 equiv of triethylamine followed by 1.1-1.5 equiv of triethylsilyl trifluoromethanesulfonate. The

resulting mixture was stirred at -78°C until completion of the reaction. Methanol was then added to quench the excess of triethylsilyl trifluoromethanesulfonate, and after 30 min a saturated aqueous NH_4Cl solution was added. The aqueous layer was separated, extracted 3 times with ether and the combined organic phases were washed with brine, dried over anhydrous MgSO_4 , filtered and concentrated *in vacuo*. The crude residue was then purified by flash chromatography on silica gel.

The synthesis of a few compounds mentioned in this paper is described in the following.

5-Triethylsiloxy-1-trimethylsilylpent-1-yne **4**

Procedure A, applied to 5-trimethylsilylpent-4-yn-1-ol (1.11 g, 7.10 mmol, 20 mL of dichloromethane, 1.2 equiv of triethylamine, 1.1 equiv of triethylsilyl chloride, 30 min), yielded 1.86 g (97%) of **4** as a colorless oil after flash chromatography (ether/petroleum ether 0:100, 5:95, 10:90, 20:80).

^1H NMR (400 MHz, CDCl_3): δ 3.69 (t, $J = 6.2$ Hz, 2H), 2.30 (t, $J = 7.0$ Hz, 2H), 1.74-1.68 (m, 2H), 0.95 (t, $J = 7.9$ Hz, 9H), 0.60 (q, $J = 7.9$ Hz, 6H), 0.13 (s, 9H).

^{13}C NMR (100 MHz, CDCl_3): δ 107.0, 84.6, 61.2, 31.6, 16.3, 6.8, 4.5, 0.2.

MS (DI, CI NH_3): m/z 271 ($\text{M}+\text{H}^+$), 133.

IR (thin film): 2955, 2912, 2876, 2734, 2176, 1459, 1415, 1387, 1349, 1320, 1286, 1249, 1187, 1106, 1072 cm^{-1} .

Anal. Calcd for $\text{C}_{14}\text{H}_{30}\text{OSi}_2$: C, 62.15 ; H, 11.18.

Found for $\text{C}_{14}\text{H}_{30}\text{OSi}_2$: C, 62.38 ; H, 11.11.

Triethyl(2-methyl-3-phenylsulfonylpropoxy)silane **6**

Procedure A, applied to 2-methyl-3-phenylsulfonylpropan-1-ol (1.09 g, 5.98 mmol, 20 mL of dichloromethane, 1.2 equiv of triethylamine, 1.1 equiv of triethylsilyl chloride, 30 min), yielded 1.68 g (95%) of **6** as a colorless oil after flash chromatography (ether/petroleum ether 0:100, 2:98, 5:95, 10:90).

^1H NMR (400 MHz, CDCl_3): δ 7.34-7.31 (m, 2H), 7.26-7.22 (m, 2H), 7.14-7.10 (m, 1H), 3.58 (dd, $J = 9.9, 5.3$ Hz, 1H), 3.52 (dd, $J = 9.9, 6.4$ Hz, 1H), 3.17 (dd, $J = 13.0, 5.6$ Hz, 1H), 2.68 (dd, $J = 13.0, 7.6$ Hz, 1H), 1.96-1.85 (m, 1H), 1.01 (d, $J = 6.7$ Hz, 3H), 0.95 (t, $J = 7.9$ Hz, 9H), 0.59 (q, $J = 7.9$ Hz, 6H).

^{13}C NMR (100 MHz, CDCl_3): δ 137.5, 128.8, 128.5, 125.5, 66.6, 37.0, 36.0, 16.4, 6.9, 4.5.

MS (DI, CI NH_3): m/z 296 ($\text{M}+\text{H}^+$), 133.

IR (thin film): 3059, 2955, 2910, 2875, 2733, 1585, 1480, 1458, 1438, 1411, 1386, 1268, 1238, 1144, 1090, 1016 cm^{-1} .

Anal. Calcd for $\text{C}_{16}\text{H}_{28}\text{OSSi}$: C, 64.80 ; H, 9.52.

Found for $\text{C}_{16}\text{H}_{28}\text{OSSi}$: C, 64.96 ; H, 9.45.

(1*R,2*S**,5*S**)-Triethyl(2-isopropyl-5-methylcyclohexyloxy)silane **8****

Procedure B, applied to (+/-)-isomenthol (335 mg, 2.23 mmol, 3 mL of dichloromethane, 1.2 equiv of triethylamine, 1.1 equiv of triethylsilyl trifluoromethanesulfonate, 2 h), yielded 555 mg (92%) of **8** as a colorless oil after flash chromatography (ether/petroleum ether 0:100, 2:98, 10:90, 20:80).

¹H NMR (400 MHz, CDCl_3): δ 3.83 (td, $J = 6.6, 3.7$ Hz, 1H), 1.98-1.83 (m, 2H), 1.66-1.59 (m, 1H), 1.50-1.30 (m, 4H), 1.21-1.09 (m, 2H), 0.96 (t, $J = 7.9$ Hz, 9H), 0.90 (d, $J = 6.7$ Hz, 3H), 0.89 (d, $J = 7.0$ Hz, 3H), 0.83 (d, $J = 6.8$ Hz, 3H), 0.58 (q, $J = 7.9$ Hz, 6H).

¹³C NMR (100 MHz, CDCl_3): δ 68.6, 49.6, 40.2, 30.5, 27.4, 25.9, 21.4, 20.8, 20.1, 7.1, 5.3.

MS (DI, CI NH_3): m/z 271 ($\text{M}+\text{H}^+$), 133.

IR (thin film): 3075, 3065, 3026, 2952, 2911, 2875, 1640, 1603, 1496, 1455, 1433, 1414, 1367, 1238, 1092, 1061, 1004 cm^{-1} .

(2,2-Dimethyl-1-phenylbut-3-enyloxy)triethylsilane **10**

Procedure A, applied to 2,2-dimethyl-1-phenylbut-3-en-1-ol (1.31 g, 7.43 mmol, 30 mL of dichloromethane, 1.3 equiv of triethylamine, 1.2 equiv of triethylsilyl chloride, 8 h), yielded 2.16 g (100%) of **10** as a colorless oil after flash chromatography (ether/petroleum ether 0:100, 5:95, 10:90).

¹H NMR (400 MHz, CDCl_3): δ 7.24-7.18 (m, 5H), 5.93 (dd, $J = 17.6, 10.8$ Hz, 1H), 4.93 (dd, $J = 10.8, 1.5$ Hz, 1H), 4.84 (dd, $J = 17.6, 1.5$ Hz, 1H), 4.35 (s, 1H), 0.97, 0.95 (2s, 6H), 0.84 (t, $J = 7.9$ Hz, 9H), 0.45 (q, $J = 7.9$ Hz, 6H).

¹³C NMR (100 MHz, CDCl_3): δ 145.7, 142.5, 128.2, 127.1, 127.0, 111.9, 82.3, 42.7, 23.7, 23.1, 6.9, 5.0.

MS (DI, CI NH_3): m/z 291 ($\text{M}+\text{H}^+$) 133.

IR (thin film): 3083, 3063, 3028, 2957, 2911, 2876, 1638, 1602, 1492, 1453, 1413, 1377, 1358, 1238, 1197, 1091, 1067, 1006 cm^{-1} .

Anal. Calcd for $\text{C}_{18}\text{H}_{30}\text{OSi}$: C, 74.42 ; H, 10.41.

Found for $\text{C}_{18}\text{H}_{30}\text{OSi}$: C, 74.52 ; H, 10.54.

(1*Z*,3*R,4*S**)-3,5-Dimethyl-4-triethylsiloxyhex-1-enyl-*N,N*-diisopropylcarbamate **11**¹**

¹ Grimaud, L.; de Mesmay, R.; Prunet, J. *Org. Lett.* **2002**, *4*, 419.

Procedure B, applied to (*1Z,3R*,4S**)-4-hydroxy-3,5-dimethylhex-1-enyl-*N,N*-diisopropylcarbamate (1.10 g, 4.05 mmol, 20 mL of dichloromethane, 1.2 equiv of triethylamine, 1.1 equiv of triethylsilyl trifluoromethanesulfonate, 30 min at -78°C then 15 min at room temperature), yielded 1.54 g (99%) of **11** as a colorless oil after flash chromatography (ether/petroleum ether 5:95, 10:90, 20:80).

¹H NMR (400 MHz, CDCl₃): δ 6.99 (d, *J* = 6.5 Hz, 1H), 4.87 (dd, *J* = 9.8, 6.5 Hz, 1H), 4.11 (s, br, 1H), 3.81 (s, br, 1H), 3.29 (dd, *J* = 6.1, 3.5 Hz, 1H), 2.88 (dq, *J* = 10.0, 6.8, 3.5 Hz, 1H), 1.75 (oct, *J* = 6.7 Hz, 1H), 1.24 (s, br, 12H), 1.00 (d, *J* = 6.9 Hz, 3H), 0.96 (t, *J* = 7.9 Hz, 9H), 0.88, 0.85 (2d, *J* = 6.7 Hz, 6H), 0.61 (q, *J* = 7.9 Hz, 6H).

¹³C NMR (100 MHz, CDCl₃): δ 153.1, 134.4, 113.2, 81.5, 46.7, 45.6, 33.6, 32.7, 21.5, 20.4, 19.5, 19.4, 18.6, 7.2, 5.6.

(1,5-Dimethyl-1-vinylhex-4-enyloxy)triethylsilane **12**

Procedure B, applied to (+/-)-linalool (1.05 g, 6.81 mmol, 8 mL of dichloromethane, 2.1 equiv of triethylamine, 1.5 equiv of triethylsilyl trifluoromethanesulfonate, 2 h), yielded 1.72 g (94%) of **12** as a colorless oil after flash chromatography (ether/petroleum ether 0:100, 2:98, 10:90, 20:80).

¹H NMR (400 MHz, CDCl₃): δ 5.85 (dd, *J* = 17.2, 10.7 Hz, 1H), 5.14 (dd, *J* = 17.2, 1.7 Hz, 1H), 5.12-5.07 (m, 1H), 4.99 (dd, *J* = 10.7, 1.7 Hz, 1H), 2.07-1.90 (m, 2H), 1.67, 1.59 (2s, 6H), 1.50-1.45 (m, 2H), 1.29 (s, 3H), 0.95 (t, *J* = 7.9 Hz, 9H), 0.58 (q, *J* = 7.9 Hz, 6H).

¹³C NMR (100 MHz, CDCl₃): δ 145.7, 131.2, 124.9, 111.8, 75.5, 43.9, 27.5, 25.8, 23.0, 17.7, 7.2, 6.9.

tert-Butyldecyloxydimethylsilane **15**

To a colorless solution of 3.00 g (18.9 mmol, 1.0 equiv) of 1-decanol in 35 mL of dichloromethane at room temperature was added 3.17 mL (22.7 mmol, 1.2 equiv) of triethylamine and 463 mg of DMAP (3.79 mmol, 0.2 equiv) followed by 3.14 g (20.8 mmol, 1.1 equiv) of *tert*-butyldimethylsilyl chloride. The resulting mixture was stirred at room temperature for 1 h 30 min. It was then treated with 2 mL of methanol and after 15 min stirring, 20 mL of a saturated aqueous NH₄Cl solution was added. The aqueous layer was separated, extracted 3 times with 70 mL of ether and the combined organic phases were washed with brine, dried over anhydrous MgSO₄, filtered and concentrated *in vacuo*. The crude residue was then purified by flash chromatography on silica gel (ether/petroleum ether 0:100, 5:95, 10:90) to afford 4.80 g (93%) of **15** as a colorless oil.

¹H NMR (400 MHz, CDCl₃): δ 3.61 (t, *J* = 6.6 Hz, 2H), 1.55-1.49 (m, 2H), 1.33-1.24 (m, 14H), 0.90 (s, 9H), 0.89 (t, *J* = 7.0 Hz, 3H), 0.06 (2s, 6H).

¹³C NMR (100 MHz, CDCl₃): δ 63.5, 33.0, 32.0, 29.8, 29.7, 29.6, 29.5, 25.9, 22.8, 26.1, 18.5, 14.3, 5.1.

6-Phenyl-4-triethylsilanyloxyhexan-1-ol

To a colorless solution of 4.00 g (13.8 mmol, 1.0 equiv) of olefine **17** in 50 mL of THF at 0°C was added 14 mL (14 mmol, 1.0 equiv) of a 1 M solution of $BH_3 \cdot THF$ and the resulting solution was stirred at 0°C for 2 h. It was then treated with 60 mL of a 3 M aqueous solution of NaOH and 60 mL of a 30% aqueous hydrogen peroxide solution. The mixture was then stirred for 14 h at room temperature to ensure completion of the oxidation and 100 mL of water was added. The aqueous layer was separated, extracted 3 times with 150 mL of ether and the combined organic phases were washed with brine, dried over anhydrous $MgSO_4$, filtered and concentrated *in vacuo*. The residue was purified by flash chromatography on silica gel (ether/petroleum ether 10:90, 20:80, 30:70, 40:60, 50:50) to afford 3.25 g (76%) of the expected primary alcohol as a colorless oil.

1H NMR (400 MHz, $CDCl_3$): δ 7.30-7.25 (m, 2H), 7.19-7.15 (m, 3H), 3.79 (quint, $J = 5.6$ Hz, 1H), 3.68-3.58 (m, 2H), 2.72-2.55 (m, 2H), 2.28 (s, br, 1H), 1.84-1.78 (m, 2H), 1.69-1.57 (m, 4H), 0.97 (t, $J = 7.9$ Hz, 9H), 0.62 (q, $J = 7.9$ Hz, 6H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 142.4, 128.5, 128.4, 125.8, 71.8, 63.2, 38.6, 33.5, 32.0, 28.3, 7.0, 5.1.

MS (DI, CI NH_3): m/z 309 ($M+H^+$), 194, 178.

IR (thin film): 3346 (br), 3084, 3061, 3026, 2951, 2911, 2875, 1603, 1496, 1455, 1414, 1377, 1238, 1097, 1059, 1007 cm^{-1} .

[6-(*tert*-Butyldimethylsiloxy)-3-triethylsiloxyhexyl]benzene **16**

To a colorless solution of 1.82 g (5.90 mmol, 1.0 equiv) of 6-phenyl-4-triethylsilanyloxyhexan-1-ol in 20 mL of dichloromethane at room temperature was added 987 μL (7.08 mmol, 1.2 equiv) of triethylamine and 144 mg of DMAP (1.18 mmol, 0.2 equiv) followed by 978 mg (6.49 mmol, 1.1 equiv) of *tert*-butyldimethylsilyl chloride. The resulting mixture was stirred at room temperature for 3 h. It was then treated with 1 mL of methanol and after 15 min stirring, 10 mL of a saturated aqueous NH_4Cl solution was added. The aqueous layer was separated, extracted 3 times with 20 mL of ether and the combined organic phases were washed with brine, dried over anhydrous $MgSO_4$, filtered and concentrated *in vacuo*. The crude residue was then purified by flash chromatography on silica gel (ether/petroleum ether 0:100, 2:98, 5:95, 10:90) to yield 2.38 g (96%) of **16** as a colorless oil.

1H NMR (400 MHz, $CDCl_3$): δ 7.30-7.16 (m, 5H), 3.77-3.72 (m, 1H), 3.63-3.60 (m, 2H), 2.75-2.67 (m, 1H), 2.64-2.57 (m, 1H), 1.82-1.71 (m, 2H), 1.62-1.51 (m, 4H), 0.97 (t, $J = 7.9$ Hz, 9H), 0.90 (s, 9H), 0.61 (q, $J = 7.9$ Hz, 6H), 0.05 (s, 6H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 142.8, 128.4, 125.8, 72.0, 63.4, 39.1, 33.5, 31.9, 28.8, 26.1, 18.5, 7.1, 5.2, -5.2.

MS (DI, CI NH_3): m/z 423 ($M+H^+$), 133.

IR (thin film): 3085, 3082, 3026, 2953, 2876, 2857, 2734, 1604, 1496, 1471, 1461, 1414, 1385, 1360, 1255, 1204, 1096, 1065, 1006 cm^{-1} .

Anal. Calcd for $C_{24}H_{46}O_2Si_2$: C, 68.18 ; H, 10.97.

Found for $C_{24}H_{46}O_2Si_2$: C, 68.01; H, 11.08.

Triethyl(1-phenethylbut-3-enyloxy)silane **17**

$C_{18}H_{30}OSi$
Mol. Wt.: 290.52

Procedure A, applied to **18** (2.69 g, 15.3 mmol, 50 mL of dichloromethane, 1.3 equiv of triethylamine, 1.2 equiv of triethylsilyl chloride, 14 h), yielded 4.37 g (99%) of **17** as a colorless oil after flash chromatography (ether/petroleum ether 0:100, 5:95, 10:90).

1H NMR (400 MHz, $CDCl_3$): δ 7.29-7.25 (m, 2H), 7.19-7.16 (m, 3H), 5.82 (ddt, J = 17.1, 10.1, 7.1 Hz, 1H), 5.11-5.01 (m, 2H), 3.80-3.74 (m, 1H), 2.72 (ddd, J = 13.6, 10.8, 5.9 Hz, 1H), 2.61 (ddd, J = 13.6, 10.8, 5.6 Hz, 1H), 2.28 (dd, J = 7.1, 6.0 Hz, 2H), 1.84-1.68 (m, 2H), 0.97 (t, J = 7.9 Hz, 9H), 0.62 (q, J = 7.9 Hz, 6H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 142.7, 135.2, 128.5, 125.8, 117.1, 71.7, 42.1, 38.8, 31.9, 7.1, 5.2.

MS (DI, CI NH_3): m/z 308 ($M+NH_4^+$), 291 ($M+H^+$), 133.

IR (thin film): 3075, 3065, 3026, 2952, 2911, 2875, 1640, 1603, 1496, 1455, 1433, 1414, 1367, 1238, 1092, 1061, 1004 cm^{-1} .

Anal. Calcd for $C_{18}H_{30}OSi$: C, 74.42 ; H, 10.41.

Found for $C_{18}H_{30}OSi$: C, 74.27 ; H, 10.33.

General procedure for triethylsilyl ether deprotection using Pd/C:

To a solution of triethylsilyl ether (*ca.* 0.4-1.0 mmol) in 3 mL of methanol or ethanol was added Pd/C (10% weight). The resulting suspension was stirred at room temperature or refluxed until completion of the reaction. It was then filtered through a plug of celite to remove palladium and charcoal residues and the resulting filtrate was concentrated *in vacuo*. The residue was purified by flash chromatography on silica gel.

All alcohols obtained - but the followings - were commercially available or previously described in the literature.

6-(*tert*-Butyldimethylsiloxy)-1-phenylhexan-3-ol

$C_{18}H_{32}O_2Si$
Mol. Wt.: 308.53

The general procedure applied to **16** (384 mg, 908 μ mol, 3 mL of methanol, 38.2 mg of Pd/C, 5 h at room temperature) yielded 275 mg (95%) of the expected secondary alcohol as a colorless oil after flash chromatography (ether/petroleum ether 20:80, 50:50).

1H NMR (400 MHz, $CDCl_3$): δ 7.30-7.25 (m, 2H), 7.22-7.15 (m, 3H), 3.70-3.60 (m, 3H), 2.80 (ddd, J = 13.9, 9.1, 6.3 Hz, 1H), 2.73-2.64 (m, 2H), 1.82-1.73 (m, 2H), 1.70-1.61 (m, 3H), 1.55-1.44 (m, 1H), 0.90 (s, 9H), 0.06 (s, 6H).

^{13}C NMR (100 MHz, CDCl_3): δ 142.5, 128.6, 128.4, 125.8, 70.8, 63.7, 39.2, 35.1, 32.3, 29.2, 26.0, 18.4, -5.3.

MS (DI, CI NH_3): m/z 309 ($\text{M}+\text{H}^+$), 291 ($\text{M}+\text{NH}_4^+-\text{H}_2\text{O}$).

IR (thin film): 3360 (br), 3085, 3062, 3026, 2950, 2926, 2856, 1603, 1496, 1471, 1454, 1387, 1360, 1255, 1097, 1031, 1005 cm^{-1} .

1-(3-Triethylsiloxyphenyl)ethanol

$\text{C}_{14}\text{H}_{24}\text{O}_2\text{Si}$
Mol. Wt.:252.42

The general procedure applied to **14** (134 mg, 365 μmol , 3 mL of methanol, 13.7 mg of Pd/C, 5 h at room temperature) yielded 78 mg (85%) of the expected secondary alcohol and 4 mg (8%) of the diol after flash chromatography (ether/petroleum ether 10:90, 30:70, 50:50, 100:0).

^1H NMR (400 MHz, CDCl_3): δ 7.21-7.17 (m, 1H), 6.95-6.93 (m, 1H), 6.88-6.87 (m, 1H), 6.76-6.74 (m, 1H), 4.82 (q, $J = 6.5$ Hz, 1H), 1.96 (s, br, 1H), 1.46 (d, $J = 6.5$ Hz, 3H), 1.00 (t, $J = 7.9$ Hz, 9H), 0.74 (q, $J = 7.9$ Hz, 6H).

^{13}C NMR (100 MHz, CDCl_3): δ 155.9, 147.7, 129.5, 118.9, 118.3, 117.0, 70.3, 25.2, 6.7, 5.1.

MS (DI, CI NH_3): m/z 270 ($\text{M}+\text{NH}_4^+$), 252 ($\text{M}+\text{NH}_4^+-\text{H}_2\text{O}$).

IR (thin film): 3342 (br), 3029, 2957, 2912, 2877, 1603, 1585, 1484, 1443, 1414, 1367, 1277, 1242, 1170, 1156, 1103, 1070, 1003 cm^{-1} .