Molecular Iodine Catalyzed Hydroxysulfenylation of Alkenes with Disulfides in Aerobic Condition

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General Methods

All chemicals were commercially available and used without further purification. Analytical thin-layer chromatography were performed on glass plates precoated with silica gel impregnated with a fluorescent indicator (254 nm). The plates were visualized by exposure to ultraviolet light. 1H NMR spectra were recorded on Bruker DRX (400 MHz) and 13C NMR spectra on Bruker DRX (100 MHz) spectrometer. Mass spectra were recorded on a Finnigan TSQ QuantumMS instrument in the electrospray ionization (ESI) mode. Elemental analyses were performed on a Yanagimoto MT3CHN recorder.

Experimental Section

Preparation of products: A 20 mL reaction vessel with a magnetic stirring bar was equipped with disulfides (0.5 mmol), alkyne (1 mmol), I2 (20 mol%), MeCN/H2O = 1:1 (2 mL). The mixture was stirred under 60°C in an air atmosphere for 2h. After the reaction, iodine was quenched by saturated solution of sodium thiosulfate and the product was extracted with ethyl acetate (3×10 mL). The combined organic phase was dried over anhydrous Na2SO4, filtered and evaporated under reduced pressure. The resulting crude product was purified by silica gel chromatography using a mixture of hexanes/ethyl acetate (4:1) as eluent to afford an analytically pure product 3.
The relative configuration of 3q was assigned according to NOESY NMR, the regioisomer of the products is trans.

The NOESY NMR Spectra of 3q

The relative configuration of 3q
Characterization data

2-((4-chlorophenyl)thio)-1-phenylethan-1-ol. 3a Colorless oil. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.40 – 7.37 (m, 4H), 7.35 (s, 2H), 7.31 – 7.29 (m, 3H), 4.84 – 4.62 (m, 1H), 3.33 – 3.11 (m, 2H), 2.76 (d, $J = 2.3$ Hz, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 142.0, 141.2, 133.6, 132.9, 131.5, 129.3, 128.7, 128.4, 128.1, 125.8, 71.9. ESI-MS: m/z = 265 [M+1]$^+$. Calc. for C$_{14}$H$_{13}$ClOS, C, 63.51; H, 4.95. Found: C, 63.63; H, 5.08.

2-((4-chlorophenyl)thio)-1-(4-fluorophenyl)ethan-1-ol. 3b Colorless oil. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.51 – 7.16 (m, 6H), 7.10 – 7.04 (m, 2H), 4.86 – 4.71 (m, 1H), 3.50 – 3.09 (m, 2H), 2.81 – 2.53 (m, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 163.7, 161.3, 137.7, 133.4, 133.1, 131.7, 129.3, 127.53, 115.5, 71.2, 44.3. $^{19}$F NMR (376 MHz, CDCl$_3$) $\delta$ -114.0. ESI-MS: m/z = 283 [M+1]$^+$. Calc. for C$_{14}$H$_{12}$ClFOS, C, 59.47; H, 4.28. Found: C, 59.30; H, 4.39.

1-(4-bromophenyl)-2-((4-chlorophenyl)thio)ethan-1-ol. 3c Colorless solid. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.54 – 7.48 (m, 2H), 7.37 – 7.23 (m, 6H), 4.83 – 4.69 (m, 1H), 3.50 – 3.06 (m, 2H), 2.81 – 2.51 (m, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 141.0, 133.2 – 131.6, 129.4, 127.5, 122.3, 121.9, 71.2, 44.3. ESI-MS: m/z = 343 [M+1]$^+$. Calc. for C$_{14}$H$_{12}$BrClOS, C, 48.93; H, 3.52. Found: C, 50.05; H, 3.47.

1-(2-chlorophenyl)-2-((4-chlorophenyl)thio)ethan-1-ol. 3e Colorless oil. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.67 – 7.64 (m, 1H), 7.42 – 7.23 (m, 7H), 5.22 – 5.12 (m, 1H), 3.70 – 3.31 (m, 2H).
2.61 (s, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 139.3, 138.6, 133.0, 131.8, 131.6, 129.7, 128.9, 127.2, 68.3, 42.3. ESI-MS: m/z = 299 [M+1]$^+$. Calc. for C$_{14}$H$_{12}$Cl$_2$OS, C,56.20; H,4.04. Found: C,56.41; H,4.15.

1-(3-chlorophenyl)-2-((4-chlorophenyl)thio)ethan-1-ol. 3f Colorless oil. $^1$H NMR (400 MHz, CDCl$_3$) δ 8.11 – 7.44 (m, 2H), 7.43 – 7.23 (m, 6H), 4.85 – 4.69 (m, 1H), 3.53 – 3.37 (m, 2H), 2.58 (s, 1H).$^{13}$C NMR (101 MHz, CDCl$_3$) δ 143.1, 134.6, 133.2, 131.8, 123.0, 129.4, 128.5, 126.0, 124.0, 71.2, 44.2. ESI-MS: m/z = 299 [M+1]$^+$. Calc. for C$_{14}$H$_{12}$Cl$_2$OS, C,56.20; H,4.04. Found: C,56.37; H,4.19.

2-((4-chlorophenyl)thio)-1-(p-tolyl)ethan-1-ol. 3g Colorless oil. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.36 (d, $J = 8.7$ Hz, 2H), 7.33 – 7.26 (m, 3H), 7.25 (s, 1H), 7.18 (d, $J = 8.0$ Hz, 2H), 4.72 (d, $J = 8.7$ Hz, 1H), 3.31 – 3.11 (m, 2H), 2.70 (d, $J = 2.5$ Hz, 1H), 2.37 (s, 3H).$^{13}$C NMR (101 MHz, CDCl$_3$) δ 139.1, 137.9, 133.8, 132.8, 131.5, 129.3, 125.8, 71.8, 44.0, 21.1. ESI-MS: m/z = 279 [M+1]$^+$. Calc. for C$_{15}$H$_{15}$ClOS, C,64.62; H,5.42. Found: C,64.51; H,5.56.

1-(4-(tert-butyl)phenyl)-2-((4-chlorophenyl)thio)ethan-1-ol. 3h Colorless oil. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.43 – 7.37 (m, 2H), 7.32 – 7.26 (m, 4H), 4.74 (d, $J = 8.8$ Hz, 1H), 3.33 – 3.14 (m, 2H), 2.80 (s, 1H), 1.35 (s, 9H).$^{13}$C NMR (101 MHz, CDCl$_3$) δ 151.2, 139.1, 133.9, 132.7, 131.4, 129.2, 125.6, 71.9, 43.8, 34.6, 31.4. ESI-MS: m/z = 321 [M+1]$^+$. Calc. for C$_{18}$H$_{21}$ClOS, C,67.38; H,6.60. Found: C,67.55; H,6.52.

2-((4-chlorophenyl)thio)-1-(4-nitrophenyl)ethan-1-ol. 3i Yellow oil. $^1$H NMR (400 MHz, CDCl$_3$) δ 8.25 – 8.19 (m, 3H), 7.60 – 7.52 (m, 3H), 7.39 – 7.28 (m, 2H), 4.95 – 4.81 (m, 1H), 3.56 – 3.28 (m, 2H), 2.78 (s, 1H).$^{13}$C NMR (101 MHz, CDCl$_3$) δ 149.2, 148.2, 147.6, 133.5, 132.7, 132.1, 129.5, 126.8, 123.9, 70.8, 44.3. ESI-MS: m/z = 310 [M+1]$^+$. Calc. for C$_{14}$H$_{12}$ClNO$_3$S, C,54.28; H,3.90. Found: C,54.19; H,3.83.
methyl 4-(2-((4-chlorophenyl)thio)-1-hydroxyethyl)benzoate. 3j Colorless oil. 
$^1$H NMR (400 MHz, CDCl$_3$) δ 8.07 – 8.02 (m, 2H), 7.48 – 7.37 (m, 4H), 7.33 – 7.16 (m, 2H), 4.91 – 4.77 (m, 1H), 3.94 (d, $J$ = 1.6 Hz, 3H), 3.54 – 3.06 (m, 2H), 2.96 – 2.66 (m, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 166.8, 147.0, 146.0, 133.2, 131.8, 130.2 – 129.7, 129.4, 125.8, 71.3, 52.2, 44.2. ESI-MS: m/z = 323 [M+1]$^+$.
Calc. for C$_{16}$H$_{15}$ClO$_3$S, C, 59.53; H, 4.68. Found: C, 59.34; H, 4.83.

2-((4-chlorophenyl)thio)-1-(naphthalen-2-yl)ethan-1-ol. 3k Colorless oil. 
$^1$H NMR (400 MHz, CDCl$_3$) δ 7.88 – 7.83 (m, 3H), 7.81 (d, $J$ = 0.4 Hz, 1H), 7.54 – 7.49 (m, 2H), 7.47 – 7.44 (m, 1H), 7.39 – 7.34 (m, 2H), 7.32 – 7.27 (m, 2H), 4.92 – 4.89 (m, 1H), 3.40 – 3.18 (m, 2H), 3.00 (s, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 139.3, 138.5, 133.6, 132.9, 132.0, 129.3, 128.6, 128.0, 127.8, 126.3, 124.9, 123.7, 123.4, 72.0, 44.1. ESI-MS: m/z = 315 [M+1]$^+$.
Calc. for C$_{18}$H$_{15}$ClOS, C, 68.67; H, 4.80. Found: C, 68.82; H, 4.94.

1-((4-chlorophenyl)thio)-2-phenylpropan-2-ol. 3l Colorless oil. 
$^1$H NMR (400 MHz, CDCl$_3$) δ 7.49 – 7.45 (m, 2H), 7.38 – 7.34 (m, 2H), 7.31 – 7.25 (m, 3H), 7.21 (d, $J$ = 8.8 Hz, 2H), 3.55 – 3.33 (m, 2H), 2.90 (s, 1H), 1.66 (s, 3H). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 146.0, 144.3, 135.1, 132.4, 131.4, 129.0, 128.4, 127.5, 127.2, 124.8, 72.7, 49.8, 24.2. ESI-MS: m/z = 279 [M+1]$^+$.
Calc. for C$_{15}$H$_{15}$ClOS, C, 64.62; H, 5.42. Found: C, 64.71; H, 5.36.

1-((4-chlorophenyl)thio)-2-(4-fluorophenyl)propan-2-ol. 3m Colorless oil. 
$^1$H NMR (400 MHz, CDCl$_3$) δ 7.33 – 7.28 (m, 2H), 7.24 – 7.06 (m, 4H), 6.91 (t, $J$ = 8.7 Hz, 2H), 3.39 (d, $J$ = 13.4 Hz, 1H), 3.21 (d, $J$ = 13.4 Hz, 1H), 2.76 (s, 1H), 1.52 (s, 3H). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 141.7, 134.8, 132.6, 131.4, 129.1, 126.6, 115.0, 73.8, 49.9, 30.4, 27.7. 19F NMR (376 MHz, CDCl$_3$) δ -115.8. ESI-MS: m/z = 297 [M+1]$^+$.
Calc. for C$_{15}$H$_{14}$ClFOS, C, 60.71; H, 4.75. Found: C, 60.54; H, 4.59.

2-((4-chlorophenyl)thio)-1,1-diphenylethan-1-ol. 3n Colorless oil. 
$^1$H NMR (400 MHz, CDCl$_3$) δ 7.36 – 7.33 (m, 4H), 7.25 – 7.10 (m, 10H), 3.75 (s, 2H), 3.36 (s, 1H). $^{13}$C NMR (101 MHz, CD$_3$OD) δ 146.0, 136.7, 131.3, 130.7, 128.4, 127.6, 126.6, 126.1, 77.4. ESI-MS: m/z = 341 [M+1]$^+$.
Calc. for C$_{20}$H$_{17}$ClOS, C, 70.47; H, 5.03. Found: C, 70.25; H, 5.13.
2-((4-chlorophenyl)thio)-1-phenylpropan-1-ol. 3o Colorless oil. \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta 7.47 – 7.41\) (m, 2H), 7.36 (d, \(J = 1.1\) Hz, 2H), 7.33 (d, \(J = 8.7\) Hz, 4H), 7.29 (d, \(J = 2.7\) Hz, 1H), 4.77 (s, 1H), 3.56 – 3.49 (m, 1H), 2.75 (d, \(J = 2.1\) Hz, 1H), 1.18 (d, \(J = 7.0\) Hz, 3H). \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta 140.7, 133.7, 132.7, 129.3, 128.3, 127.6, 126.0, 73.6, 51.7, 13.4\). ESI-MS: \(m/z = 279\) [M+1]\(^+\). Calc. for C\(_{15}\)H\(_{15}\)ClOS, C, 64.62; H, 5.42. Found: C, 64.88; H, 5.65.

2-((4-chlorophenyl)thio)-1,2-diphenylethan-1-ol. 3p Colorless oil. \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta 7.30 – 7.20\) (m, 10H), 7.15 (s, 4H), 5.07 – 5.05 (m, 1H), 4.41 (t, \(J = 4.7\) Hz, 1H), 2.44 (d, \(J = 3.0\) Hz, 1H). \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta 140.5, 137.6, 133.7, 129.0, 128.4, 128.1, 127.8, 126.8, 76.3\). ESI-MS: \(m/z = 341\) [M+1]\(^+\). Calc. for C\(_{20}\)H\(_{17}\)ClOS, C, 70.47; H, 5.03. Found: C, 70.34; H, 5.11.

2-((4-chlorophenyl)thio)cyclopentan-1-ol. 3q Colorless oil. \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta 7.33\) (d, \(J = 8.7\) Hz, 2H), 7.26 (d, \(J = 8.7\) Hz, 2H), 3.27 – 3.44 (m, 1H), 2.70-2.68 (m, 1H), 1.67 – 1.60 (m, 2H), 1.25 – 1.16 (m, 4H). \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta 134.3, 132.5, 131.9, 129.1, 82.1, 78.4, 54.1, 35.7, 34.2, 33.4, 31.0, 22.1, 21.9\). ESI-MS: \(m/z = 243\) [M+1]\(^+\). Calc. for C\(_{12}\)H\(_{15}\)ClOS, C, 59.37; H, 6.23. Found: C, 59.52; H, 6.36.

1-((4-chlorophenyl)thio)-4-methylpentan-2-ol. 3r Colorless oil. \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta 7.42 – 7.30\) (m, 2H), 7.28 (t, \(J = 4.4\) Hz, 2H), 3.86 – 3.69 (m, 1H), 3.40 – 3.24 (m, 2H), 2.88 – 2.83 (m, 1H), 1.52 – 1.48 (m, 1H), 1.35 – 1.32 (m, 2H), 0.95 – 0.89 (m, 6H). \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta 134.1, 132.6, 131.3, 129.2, 69.2, 67.7, 45.7, 45.3, 43.0, 24.9, 23.2, 22.1, 17.4\). ESI-MS: \(m/z = 245\) [M+1]\(^+\). Calc. for C\(_{12}\)H\(_{15}\)ClOS, C, 58.88; H, 7.00. Found: C, 59.09; H, 69.85.

4-bromo-1-((4-chlorophenyl)thio)butan-2-ol. 3s Colorless oil. \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta 7.34 – 7.31\) (m, 2H), 7.31 – 7.27 (m, 2H), 4.12 – 4.07 (m, 1H), 3.97 (d, \(J = 7.2\) Hz, 1H), 3.95 – 3.80 (m, 2H), 3.80 – 3.71 (m, 1H), 3.70 – 3.67 (m, 1H), 2.37 – 2.32 (m, 1H), 1.95 – 1.90 (m, 1H). \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta 135.8, 132.6, 131.3, 129.2, 69.2, 67.7, 45.7, 45.3, 43.0, 24.9, 23.2, 22.1, 17.4\). ESI-MS: \(m/z = 245\) [M+1]\(^+\). Calc. for C\(_{12}\)H\(_{15}\)ClOS, C, 58.88; H, 7.00. Found: C, 59.09; H, 69.85.
MHz, CDCl$_3$) δ 134.1, 132.9, 132.0, 129.2, 73.5, 67.6, 45.1, 33.1. ESI-MS: m/z = 295 [M+1]$^+$. Calc. for C$_{10}$H$_{12}$BrClOS, C,40.63; H,4.09. Found: C,40.54; H,4.17.

![image]

1-phenyl-2-(phenylthio)ethan-1-ol. 3t Colorless oil. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.47 – 7.45 (m, 2H), 7.41 – 7.37 (m, 5H), 7.35 (d, $J$ = 1.5 Hz, 1H), 7.34 – 7.33 (m, 1H), 7.28 (d, $J$ = 7.4 Hz, 1H), 4.78 – 7.74 (m, 1H), 3.38 – 3.11 (m, 2H), 2.98 (s, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 142.2, 135.0, 130.2, 129.2, 128.6, 128.0, 126.8, 125.9, 71.8, 44.0. ESI-MS: m/z = 231 [M+1]$^+$. Calc. for C$_{14}$H$_{14}$OS, C,73.01; H,6.13. Found: C,73.21; H,6.24.

![image]

1-phenyl-2-(p-tolylthio)ethan-1-ol. 3u Colorless oil. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.41 – 7.40 (m, 1H), 7.38 (d, $J$ = 4.2 Hz, 5H), 7.35 – 7.33 (m, 1H), 7.18 (d, $J$ = 7.9 Hz, 2H), 4.74 – 4.71 (m, 1H), 3.33 – 3.29 (m, 1H), 3.11 – 3.06 (m, 2H), 2.39 (s, 3H). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 142.3, 137.1, 131.1, 130.0, 128.6, 128.0, 125.9, 71.6, 44.8, 21.1. ESI-MS: m/z = 245 [M+1]$^+$. Calc. for C$_{15}$H$_{16}$OS, C,73.73; H,6.60. Found: C,73.91; H,6.44.

![image]

2-((3,5-dimethylphenyl)thio)-1-phenylethan-1-ol. 3v Colorless oil. $^1$H NMR (400 MHz, MeOD) δ 7.37 – 7.26 (m, 5H), 6.95 (s, 2H), 6.83 (s, 1H), 4.73 (t, $J$ = 6.5 Hz, 1H), 3.34 – 3.31 (m, 1H), 3.23 – 3.15 (m, 2H), 2.26 (s, 6H). $^{13}$C NMR (101 MHz, CD$_3$OD) δ 143.3, 138.3, 135.8, 127.9, 127.5, 127.3, 126.9, 125.9, 72.4, 42.2, 19.9. ESI-MS: m/z = 259 [M+1]$^+$. Calc. for C$_{16}$H$_{18}$OS, C,74.38; H,7.02. Found: C,74.50; H,7.11.

![image]

2-((4-fluorophenyl)thio)-1,1-diphenylethan-1-ol. 3w Colorless oil. $^1$H NMR (400 MHz, CDCl$_3$) δ 7.44 – 7.40 (m, 4H), 7.34 – 7.22 (m, 8H), 6.94 – 6.88 (m, 2H), 3.81 (s, 2H), 3.54 (s, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 163.6, 159.7, 145.1, 133.2, 133.1, 128.3, 127.4, 126.2, 116.3, 116.0, 77.7, 50.3. 19F NMR (376 MHz, CDCl$_3$) δ -114.5. ESI-MS: m/z = 325 [M+1]$^+$. Calc. for C$_{20}$H$_{15}$FOS, C,74.05; H,5.28. Found: C,73.87; H,5.12.
2-((4-bromophenyl)thio)-1,1-diphenylethan-1-ol. Colorless oil. $^1$H NMR (300 MHz, CDCl$_3$) δ 7.44 – 7.41 (m, 4H), 7.36 – 7.19 (m, 10H), 3.84 (d, $J = 5.0$ Hz, 2H), 3.42 (s, 1H). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 145.0, 135.7, 131.9, 128.4, 127.5, 126.1, 120.6, 77.7, 49.1. ESI-MS: m/z = 385 [M+1]$^+$. Calc. for C$_{20}$H$_{17}$BrOS, C,62.34; H,4.45. Found: C,62.22; H,4.32.