

Supplementary Information

Designer μ -oxo-bridged hypervalent iodine(III) organocatalysts for greener oxidations

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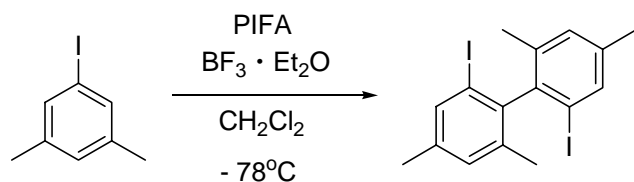
General Information

^1H NMR and ^{13}C NMR spectra were recorded by a JEOL JMN-300 or EX-270 spectrometer in CDCl_3 otherwise noted. Data are reported as follows: chemical shift in ppm (δ), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, br = broad singlet, m = multiplet), coupling constant (Hz), and integration. Infrared spectra (IR) were obtained using a Hitachi 270-50 spectrometer; absorptions are reported in reciprocal centimeters for strong and structurally important peaks. Mass spectra were obtained on a Shimadzu GCMS-QP 5000 instrument with ionization voltages of 70 eV. High resolution mass spectra and elemental analyses were performed by the Elemental Analysis Section of Osaka University.

Materials

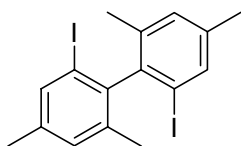
All solvents were obtained from commercial suppliers used without further purification. Peracetic acid (PAA), hexafluoroisopropanol (HFIP), and $\text{PhI}(\text{OAc})_2$ (PIDA) are commercially available. The starting materials **3a-3k** were prepared from corresponding acid chlorides by condensation with methoxyamine hydrochloride or N-aminophthalimide.

1. Synthesis of bis(iodoarene) catalyst **2a**



To a stirred solution of 3,5-dimethyliodobenzene (7 mmol) in CH₂Cl₂ (8.75 ml) was added dropwise to a solution of PIFA (3.5 mmol) and BF₃ · Et₂O (7 mmol) in CH₂Cl₂ (8.75 ml) under nitrogen atmosphere at -78 °C. The reaction mixture was stirred at the same temperature for 5 h. After the reaction, the obtained mixture was quenched with saturated aqueous NaHCO₃ and the aqueous layer was extracted with CH₂Cl₂. The combined organic layers were washed with brine, and dried over anhydrous Na₂SO₄. After removal of the solvent, the residue was purified by column chromatography on silica gel (eluent: AcOEt/*n*-hexane) to give **2a** (1.02 g, 63%).

2,2'-Diiodo-4,4',6,6'-tetramethylbiphenyl (**2a**)¹⁾



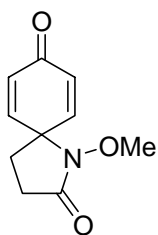
¹H NMR (CDCl₃): δ= 1.95 (s, 6H), 2.31 (s, 6H), 7.06 (s, 2H), 7.62 (s, 2H) ppm; ¹³C NMR (CDCl₃): δ= 20.4, 21.2, 100.7, 130.7, 136.9, 137.0, 139.0, 144.3 ppm; IR (KBr): 3014, 1599, 1541, 1035 cm⁻¹

Bis(iodoarene) **2b** is commercially available compound. Other bis(iodoarene) catalysts, **2c** and **2d**, were obtained from iodination of the corresponding 2,2'-diamino-6,6'-disubstituted biphenyl, which were synthesized by literature procedures.²⁾

2. General experimental procedure for green oxidation using bis(iodoarene)catalyst **2a**

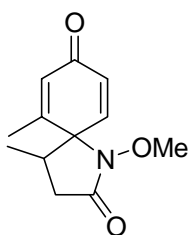
To a stirred solution of 2,2'-diiodo-4,4',6,6'-tetramethylbiphenyl **2a** (1.4 mg, 0.003 mmol) and amide **3a** (31.4 mg, 0.15 mmol) in HFIP (1.2 ml) and CH₂Cl₂ (1.2 ml) was added 9% peracetic acid (0.23 ml, 0.3 mmol) under air. The reaction was performed at 35°C for 2.5 h. After the reaction, the solvents were removed under reduced pressure. The residue was extracted with CH₂Cl₂, washed with water and saturated aqueous NaHCO₃, and then dried over anhydrous Na₂SO₄. After evaporation, almost pure product **4a** (27.0 mg, 93%) was obtained, which was purified by column chromatography on silica gel.

1-Methoxy-1-azaspiro[4.5]deca-6,9-diene-2,8-dione (**4a**)³⁾



White crystals; mp 130-131 °C; ¹H NMR (CDCl₃): δ 2.18 (t, *J* = 7.8 Hz, 2H), 2.56 (t, *J* = 7.8 Hz, 2H), 3.80 (s, 3H), 6.39 (d, *J* = 10.2 Hz, 2H), 6.84 (d, *J* = 10.2 Hz, 2H) ppm; ¹³C NMR (CDCl₃): δ 25.9, 27.5, 61.9, 65.3, 131.1, 147.2, 171.7, 184.4 ppm; IR (KBr): 2358, 2341, 1743, 1672, 1278, 711 cm⁻¹; HRMS(FAB): Calcd for C₁₀H₁₁NO₃ (M + H)⁺: 194.0739. Found: 194.0816.

1-Methoxy-4,6-dimethyl-1-azaspiro[4.5]deca-6,9-diene-2,8-dione (**4b**)³⁾

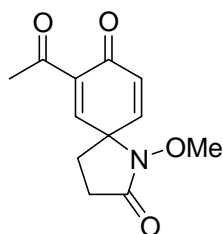


White crystals; mp 92-93 °C; ¹H NMR (CDCl₃): δ 0.97 (d, *J* = 6.9 Hz, 3H), 2.10 (s, 3H), 2.22 (dd, *J* = 16.5, 10.2 Hz, 1H), 2.55-2.63 (m, 1H), 2.72 (dd, *J* = 16.5, 8.4 Hz, 1H), 3.80 (s, 3H), 6.34 (s, 1H), 6.44 (dd, *J* = 10.2, 2.1 Hz, 1H), 6.75 (d, *J* = 10.2 Hz, 1H) ppm; ¹³C

NMR (CDCl₃): δ 14.6, 18.5, 33.4, 34.8, 63.8, 68.6, 131.4, 131.9, 145.7, 155.7, 171.9, 184.5 ppm;

IR (KBr): 3500, 2972, 1714, 1666, 1286 cm⁻¹; MS *m/z*: 221 (M⁺).

7-Acetyl-1-methoxy-1-azaspiro[4.5]deca-6,9-diene-2,8-dione (4c)³⁾



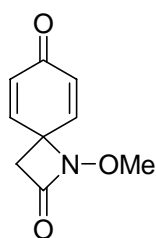
Colorless oil; ¹H NMR (CDCl₃): δ 2.19-2.26 (m, 2H) 2.57 (s, 3H), 2.59-2.63

(m, 2H), 3.78 (s, 3H), 6.41 (d, *J* = 10.2 Hz, 1H), 6.87 (dd, *J* = 10.2, 3.0 Hz, 1H), 7.42 (d, *J* = 3.0

Hz, 1H) ppm; ¹³C NMR (CDCl₃): δ 25.6, 27.0, 30.5, 61.9, 65.0, 131.2, 139.2, 146.2, 150.6, 171.1,

181.9, 196.6 ppm; IR (KBr): 2939, 1693, 1666, 1359, 1257 cm⁻¹; MS *m/z*: 235 (M⁺).

1-Methoxy-1-azaspiro[3.5]nona-5,8-diene-2,7-dione (4d)



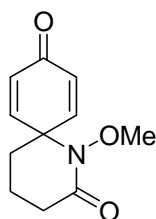
White crystals; mp 109-110 °C; ¹H NMR (CDCl₃): δ 2.98 (s, 2H) 3.78 (s, 3H),

6.47 (d, *J* = 9.9 Hz, 2H), 6.93 (d, *J* = 9.9 Hz, 2H) ppm; ¹³C NMR (CDCl₃): δ 43.5, 60.4, 65.4,

132.3, 145.6, 162.1, 184.2 ppm; IR (KBr): 3523, 2941, 1770, 1666, 1402 cm⁻¹; HRMS(FAB):

Calcd for C₉H₉NO₃ (M + H)⁺: 180.0582. Found: 180.0660.

1-Methoxy-1-azaspiro[5.5]undeca-7,10-diene-2,9-dione (4e)

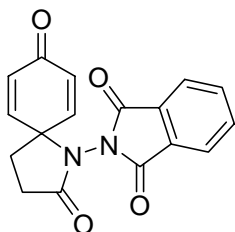


White crystals; mp 112.6-112.7 °C; ¹H NMR (CDCl₃): δ 1.91-1.99 (m, 2H),

2.03-2.06 (m, 2H), 2.61 (d, *J* = 6.3 Hz, 2H), 3.74 (s, 3H), 6.34 (d, *J* = 9.9 Hz, 2H), 6.94 (d, *J* =

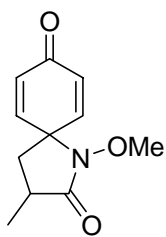
9.9 Hz, 2H) ppm; ^{13}C NMR (CDCl_3): δ 18.3, 33.2, 35.6, 63.6, 64.5, 130.0, 148.7, 168.1, 184.4 ppm; IR (KBr): 3506, 2939, 2358, 2341, 1668, 1392, 862 cm^{-1} ; HRMS(FAB): Calcd for $\text{C}_{11}\text{H}_{13}\text{NO}_3$ ($\text{M} + \text{H}$) $^+$: 208.0895. Found: 208.0968.

1-(1,3-Dihydro- 1,3-dioxo-2H-isoindol-2-yl)-1-azaspiro[4.5]deca-6,9-diene-2,8-dione (4f)



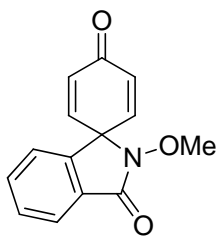
White crystals: mp 255-258 $^{\circ}\text{C}$; ^1H NMR (CDCl_3): δ 2.46 (t, $J = 8.0$ Hz, 2H), 2.80 (t, $J = 8.0$ Hz, 2H), 6.27 (dd, $J = 10.1, 2.7$ Hz, 2H), 7.12 (dd, $J = 10.1, 2.7$ Hz, 2H), 7.78-7.84 (m, 2H), 7.85-7.91 (m, 2H) ppm; ^{13}C NMR (CDCl_3): δ 21.6, 24.0, 57.5, 119.0, 124.5, 125.2, 129.9, 141.7, 159.4, 166.0, 179.1 ppm; IR (KBr): 1805, 1750, 1730, 1675, 715 cm^{-1} ; HRMS(FAB): Calcd for $\text{C}_{17}\text{H}_{12}\text{N}_2\text{O}_4$ ($\text{M} + \text{H}$) $^+$: 309.0797. Found: 309.0889; Anal. Calcd for $\text{C}_{17}\text{H}_{12}\text{N}_2\text{O}_4$: C, 66.23; H, 3.92; N, 9.09. Found: C, 66.00; H, 4.10; N, 9.15.

1-Methoxy-3-dimethyl-1-azaspiro[4.5]deca-6,9-diene-2,8-dione (4g)



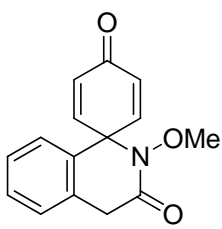
White crystals; mp 105.7-106.7 $^{\circ}\text{C}$; ^1H NMR (CDCl_3): δ 1.29 (d, $J = 7.1$ Hz, 3H), 1.82 (dd, $J = 13.2, 9.5$ Hz, 1H), 2.28 (dd, $J = 13.2, 9.0$ Hz, 1H), 2.58-2.64 (m, 1H), 3.75 (s, 3H), 6.34 (d, $J = 10.7$ Hz, 2H), 6.78 (d, $J = 10.8$, 2H) ppm; ^{13}C NMR (CDCl_3): δ 17.2, 32.8, 37.1, 61.6, 65.8, 131.4, 131.9, 147.4, 149.1, 174.7, 185.0 ppm; IR (KBr): 2938, 1719, 1672, 1250, 714 cm^{-1} ; HRMS(FAB): Calcd for $\text{C}_{11}\text{H}_{13}\text{NO}_3$ ($\text{M} + \text{H}$) $^+$: 208.0895. Found: 208.0977.

Product 4h



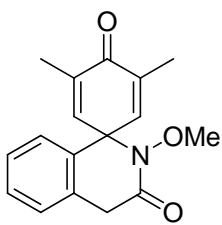
White crystals; mp 203.8-205.8 °C; ^1H NMR (CDCl_3): δ 3.96 (s, 3H), 6.55 (d, $J = 9.5$ Hz, 2H), 6.67 (d, $J = 9.5$ Hz, 2H), 7.23 (d, $J = 7.6$ Hz, 1H), 7.59-7.65 (m, 2H), 7.95 (d, $J = 7.6$ Hz, 1H) ppm; ^{13}C NMR (CDCl_3): δ 65.1, 66.1, 122.7, 124.9, 129.3, 130.1, 131.6, 133.5, 139.3, 145.6, 165.4, 184.6 ppm; IR (KBr): 3039, 2941, 1719, 1671, 1605 cm^{-1} ; HRMS(FAB): Calcd for $\text{C}_{14}\text{H}_{12}\text{NO}_3$ ($\text{M} + \text{H}$) $^+$: 242.0817. Found: 242.0830.

Product 4i



White crystals; mp 209-210 °C; ^1H NMR (CDCl_3): δ 3.79 (s, 3H), 3.87 (s, 2H), 6.34(d, $J = 9.9$ Hz, 2H), 6.78(d, $J = 9.9$ Hz, 2H), 7.05-7.29 (m, 4H) ppm; ^{13}C NMR (CDCl_3): δ 36.3, 64.8, 67.0, 126.3, 127.6, 128.5, 129.2, 129.3, 130.2, 147.5, 166.1, 184.7 ppm; IR (KBr): 2936, 1667, 1629, 1604, 1350, 1060, 683 cm^{-1} ; MS m/z : 255 (M^+); HRMS(FAB): Calcd for $\text{C}_{15}\text{H}_{14}\text{NO}_3$ ($\text{M} + \text{H}$) $^+$: 256.0974. Found: 256.0970.

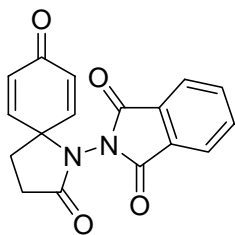
Product 4j



White crystals; mp 186-187 °C; ^1H NMR (CDCl_3): δ 1.91 (s, 6H), 3.75 (s, 3H), 3.83 (s, 2H), 6.53 (s, 2H), 6.97-7.27 (m, 4H) ppm; ^{13}C NMR (CDCl_3): δ 15.9, 36.4, 64.7, 67.2, 126.2, 127.4, 128.3, 128.9, 130.1, 131.0, 135.9, 142.6, 166.4, 186.3 ppm; IR (KBr): 2958, 2931, 1693, 1643, 1633, 1059, 761 cm^{-1} ; MS m/z : 283 (M^+); HRMS(FAB): Calcd for $\text{C}_{17}\text{H}_{18}\text{NO}_3$

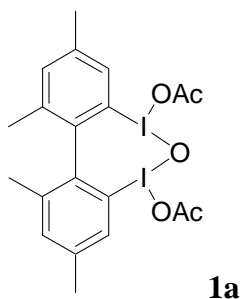
(M + H)⁺: 284.1287. Found: 284.1299.

1-(1,3-Dihydro-1,3-dioxo-2H-isoindol-2-yl)-1-azaspiro[4.5]deca-6,9-diene-2,8-dione (4f)



White crystals: mp 255-258 °C; ¹H NMR (CDCl₃): δ 2.46 (t, *J* = 8.0 Hz, 2H), 2.80 (t, *J* = 8.0 Hz, 2H), 6.27 (dd, *J* = 10.1, 2.7 Hz, 2H), 7.12 (dd, *J* = 10.1, 2.7 Hz, 2H), 7.78-7.84 (m, 2H), 7.85-7.91 (m, 2H) ppm; ¹³C NMR (CDCl₃): δ 21.6, 24.0, 57.5, 119.0, 124.5, 125.2, 129.9, 141.7, 159.4, 166.0, 179.1 ppm; IR (KBr): 1805, 1750, 1730, 1675, 715 cm⁻¹; HRMS(FAB): Calcd for C₁₇H₁₂N₂O₄ (M + H)⁺: 309.0797. Found: 309.0889; Anal. Calcd for C₁₇H₁₂N₂O₄: C, 66.23; H, 3.92; N, 9.09. Found: C, 66.00; H, 4.10; N, 9.15.

3. Synthesis of *μ*-oxo-bridged reactive hypervalent iodine(III) compounds **1a**



To a stirred solution of SelectfluorTM (2.69 g, 7.6 mmol) in MeCN (47.5 ml) was successively added AcOH (17.1 ml) and 2,2'-diiodo-4,4',6,6'-tetramethylbiphenyl **2a** (0.88 g, 1.9 mmol) under air atmosphere, and the mixture was stirred overnight at room temperature. After removal of MeCN under reduced pressure, the resulting residue was extracted with CH₂Cl₂, and then the organic solution was dried over anhydrous Na₂SO₄. After evaporation of the solvent, the crude solid **1a** was dissolved in minimal amount of CH₂Cl₂, which was added dropwise to a stirred hexane. The resulting suspension was filtered to give pure product **1a** (1.09 g, 96%).

The use of PAA instead of SelectfluorTM as oxidant also afforded **1a** in similar yield.

1a: White powder; mp 157 °C; ¹H NMR (CDCl₃): δ 1.85 (s, 6H), 2.16 (s, 6H), 2.46 (s, 6H), 7.38 (s, 2H), 7.86 (s, 2H) ppm; ¹³C NMR (CDCl₃): δ 21.2 (x 2), 21.4, 127.0, 133.4, 135.2, 137.7, 139.2, 142.8, 177.6 ppm; IR (KBr): 1649, 1559, 1018, 750 cm⁻¹.

A pure sample compatible for X-ray crystallographic analysis was obtained by recrystallization from acetonitrile-hexane. For crystallographic data of **1a** in CIF, see CCDC 779814.

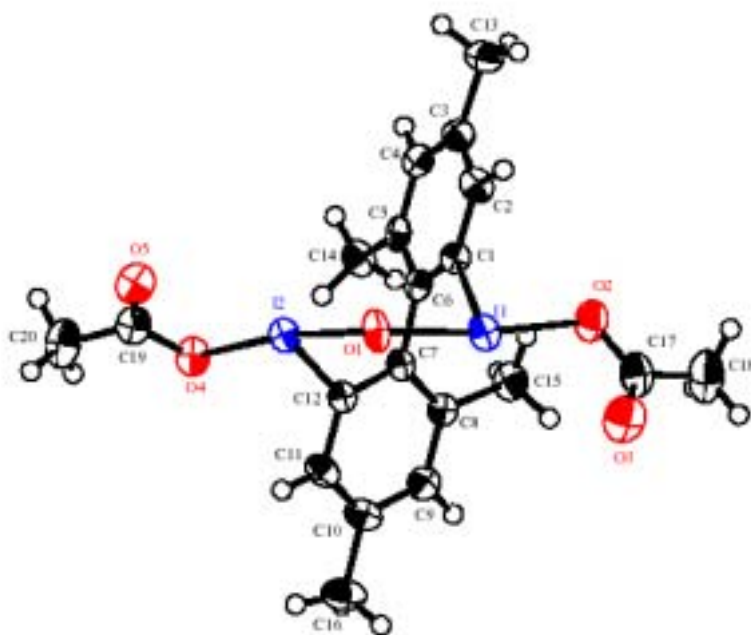


Figure 1. X-ray crystal structure of compound **1a**.

4. Stoichiometric reaction of 3a leading to 4a using the prepared 1a

To a stirred solution of amide **3a** (10.5 mg, 0.05 mmol) in wet HFIP (0.5 ml) and CH₂Cl₂ (0.5 ml) was added the prepared **1a** (14.9 mg, 0.025 mmol) at room temperature under air. After 3 h, the solvents were removed under reduced pressure. The organic layer was then washed with water, saturated aqueous NaHCO₃, and dried over anhydrous Na₂SO₄. After evaporation, a crude product **4a** (8.7 mg, 90%) was obtained by the standard purification procedure.

References

- 1) H. Tohma, M. Iwata, T. Maegawa and Y. Kita, *Tetrahedron Lett.*, 2002, **43**, 9241.
- 2) a) K. M. Gillespie, C. J. Sanders, P. O'Shaughnessy, I. Westmoreland, C. P. Thickitt and P. Scott, *J. Org. Chem.*, 2002, **67**, 3450. b) J. Sohn, B. Kiburz, L. Zhitao, D. Liu, A. Safi, M. C. Pirrung and J. Rudolph, *J. Med. Chem.*, 2003, **46**, 2580.
- 3) T. Dohi, A. Maruyama, Y. Minamitsuji, N. Takenaga and Y. Kita, *Chem. Commun.*, 2007, 1224.