Supporting Information

Regioselective Oxybromination of Benzene and Its Derivatives by Bromide Anion with a Mononuclear Nonheme Mn(IV)-Oxo Complex

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Experimental Section

Materials. Commercially available chemicals were used without further purification unless otherwise indicated. Benzene and its derivatives, such as 1,2,4-trimethoxybenzene, 1,3,5-trimethoxybenzene, 1,2-dimethoxybenzene, 1,4-dimethoxybenzene, 1-methyl-3,4-dimethoxybenzene, and scandium(III) triflate (Sc(CF$_3$SO$_3$)$_3$) were purchased from Aldrich Chemical Co. and used as received. Solvents were dried according to published procedures and distilled under Argon prior to use.$^{S1}$ Iodosylbenzene (PhIO) was prepared by literature method.$^{S2}$ Mn$^{II}$(CF$_3$SO$_3$)$_2$•2CH$_3$CN was prepared by literature method.$^{S3}$ Ligand (Bn-TPEN = N-benzyl-N,N',N'-tris(2-pyridylmethyl)-1,2-diaminoethane) and [(Bn-TPEN)Mn$^{II}$]$^{2+}$ complex were synthesized according to the literature methods.$^{S4}$ [(Bn-TPEN)Mn$^{IV}$(O)-(Sc(OTf)$_3$)$_2$]$^{2+}$ was generated as reported previously.$^{S5,S6}$

Instrumentation. UV-vis spectra were recorded on a Hewlett Packard 8453 diode array spectrophotometer equipped with a UNISOKU Scientific Instruments Cryostat USP-203A for the reactions of [(Bn-TPEN)Mn$^{IV}$(O)-(Sc(OTf)$_3$)$_2$]$^{2+}$ (1) with a substrate or on a UNISOKU RSP-601 stopped-flow spectrometer equipped with a MOS-type highly sensitive photodiode-array. Electrospray ionization mass spectra (ESI-MS) were collected on a Thermo Finnigan (San Jose, CA, USA) LCQTM Advantage MAX quadrupole ion trap instrument, by infusing samples directly into the source at 20 μL/min using a syringe pump. The spray voltage and the capillary temperature were set at 4.7 kV and 120 °C, respectively. X-band electron paramagnetic resonance (EPR) spectra were taken at 77 K using a JEOL X-band EPR spectrometer (JES-FA100). The experimental parameters for EPR measurements with a JES-FA100 were as follows: microwave frequency = 9.047 GHz, microwave power = 1.0 mW, modulation amplitude = 1.0 mT, modulation frequency = 100 kHz and time constant = 0.03 s. $^1$H nuclear magnetic resonance (NMR) spectra were measured with a Bruker model digital AVANCE III 400 FT-NMR spectrometer. Product analysis was performed with an Agilent Technologies 6890N gas chromatograph (GC).

Kinetic Measurements. All the reactions were performed in a 1.0 cm quartz cuvette and followed by monitoring absorption spectral changes due to formation of the radical cation of 1,3,5-trimethoxybenzene in the reaction of 1 (0.25 mM) with 1,3,5-trimethoxybenzene (2.5 – 10 mM) in trifluoroethanol (TFE)/acetonitrile (MeCN) (v/v = 1:1) at 273 K. The rate of formation

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of the radical cation of 1,3,5-trimethoxybenzene obeyed first-order kinetics under pseudo-first-order conditions (i.e., \[ \frac{[1,3,5\text{-trimethoxybenzene}]}{[((\text{Bn-TPEN})\text{Mn}^{IV}(O))^2+-(\text{Sc(OTf)}_3)_2]} > 10 \). The second-order rate constant was determined from the slope of a plot of the pseudo-first-order rate constant vs concentration of 1,3,5-trimethoxybenzene. The same procedure was used for the oxidation of 1,2-dimethoxybenzene, 1,4-dimethoxybenzene and 1-methyl-3,4-dimethoxybenzene by 1. However, for the oxidation of 1,2,4-trimethoxybenzene (0.50 mM) by 1 (0.50 mM) in TFE/MeCN (v/v = 1:1) at 273 K, the second-order plot of 1/[1] vs time was employed to determine the second-order rate constant.

Nanosecond time-resolved transient absorption measurements of 1 were performed using the laser system provided by UNISOKU Co., Ltd. A mixture solution containing 1 in a quartz cell (1 cm × 1 cm) was excited by a Nd:YAG laser (Continuum SLII-10, 4-6 ns fwhm, \( \lambda_{ex} = 355 \) nm, 80 mJ pulse\(^{-1} \), 10 Hz). The photodynamics were monitored by continuous exposure to a xenon lamp for visible region and halogen lamp for near-IR region as a probe light and a photomultiplier tube (Hamamatsu 2949) as a detector.

**Product Analysis.** The oxybromination of methoxy-substituted benzene derivatives by 1 was examined in a quartz cell (optical path length 1.0 cm) at 273 K. Products formed in the bromination of benzene derivatives (20 mM) by \[ ((\text{Bn-TPEN})\text{Mn}^{II})^2+ \] (0.10 mM) with PhIO (10 mM) in the presence of \( \text{Sc(OTf)}_3 \) (20 mM) and TBABr (10 mM) in TFE/MeCN (v/v = 1:1) after 45 minutes were identified by \(^1\text{H} \) NMR by comparison of the chemical shifts of the products with respect to those of authentic samples, and the product yields were determined by comparing the responsive peak areas of reaction products against area of known authentic compounds using internal standard benzene. Monobromination was obtained as a sole product with the range of 72 – 93% yields based on amount of PhIO used.

The halogenation of benzene by the excited state of 1 was examined in a quartz cell (optical path length 1.0 cm) using a Xe lamp (300 W) on an ASAHI SPECTRA MAX-302 for irradiation at 273 K. Products formed in the oxyhalogenation of benzene (500 mM) by the photoexcited state of 1 (0.50 mM) in presence of TBABr (3.0 mM) in TFE/MeCN (v/v = 1:1) after irradiation with a Xe lamp (300 W) for 20 minutes was identified by GC by comparison of the retention time of the products with respect to authentic samples, and the product yields were determined by comparing the responsive peak areas of reaction products against area of known authentic compounds.
compounds using internal standard decane. Bromobenzene was obtained as a sole product with 92(2)\% yield (based on amount of 1 used) under an argon atmosphere.

**EPR Simulation of TMeOB**. The optimized simulation of the EPR spectrum of TMeOB\(^{++}\) obtained in the oxidation of TMeOB (0.25 mM) by 1 (0.25 mM) (microwave frequency 9.047 GHz, modulation frequency 100 kHz, modulation amplitude 1.0 mT, microwave power 1.0 mW time constant = 0.03 s) was performed with the simulation parameters, such as hyperfine coupling constants (mT), \(a_H = 0.245\) (for 7H), 0.10 (for 3H), 0.05 (for 2H) and maximum slope linewidth, \(\Delta H_{\text{msl}} = 0.11\) mT. Similarly, the hyperfine coupling constants (\(a_H\)) and the maximum slope linewidths (\(\Delta H_{\text{msl}}\)) were determined from computer simulation of the EPR spectrum of TMeOB\(^{++}\) in the oxidation of TMeOB with different concentrations (0.50 mM – 1.75 mM) by 1 (0.25 mM). The rate constant of the self-exchange electron transfer reactions between TMeOB and TMeOB\(^{++}\) was determined by exchange broadening of EPR lines. The \(\Delta H_{\text{msl}}\) value determined increased linearly with an increase in TMeOB concentration.

**Calculation Details.** Density functional theory (DFT)\(^{57}\) calculations were performed using the B3LYP functional\(^{58}\) as implemented in the Gaussian 09 (G09) package.\(^{59}\) The geometry optimizations for 1,2-dimethoxybenzene radical cation, 1-methyl-3,4-dimethoxybenzene radical cation and 1,2,4-trimethoxybenzene radical cation were performed at the B3LYP/6-31G\(^*\)\(^{**}\)(all)\(^{510}\) level of theory. Natural bond orbital (NBO) analysis was done with NBO program Version 3.1.\(^{511}\) Natural population analysis (NPA) charges were then calculated to understand the regioselective bromination of these radical cation species with Br\(^-\) at the most stable geometry.
Table S1. Natural Population Analysis (NPA) Charges of 1,2-Dimethoxybenzene Radical Cation, 1-Methyl-3,4-dimethoxybenzene Radical Cation and 1,2,4-Trimethoxybenzene Radical Cation Calculated at the B3LYP/6-31G** Level

<table>
<thead>
<tr>
<th>radial cation</th>
<th>position of carbon atom</th>
<th>charge</th>
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<tbody>
<tr>
<td><img src="image" alt="Radical Cation 1,2-Dimethoxybenzene" /></td>
<td>C4/C5</td>
<td>0.013</td>
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<tr>
<td><img src="image" alt="Radical Cation 1-Methyl-3,4-dimethoxybenzene" /></td>
<td>C3/C6</td>
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<td>C2</td>
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<td></td>
<td>C5</td>
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<tr>
<td></td>
<td>C6</td>
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<td><img src="image" alt="Radical Cation 1,2-Dimethoxybenzene" /></td>
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<tr>
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<td><img src="image" alt="Radical Cation 1,2,4-Trimethoxybenzene" /></td>
<td>C6</td>
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Table S2. One-Electron Oxidation Potentials ($E_{ox}$) of Substrates (S), Methoxy-Substituted Benzenes and Coordinatively Saturated Metal Complexes, and Second–Order Rate Constants of ET from S to 1 in TFE/MeCN (v/v = 1:1) at 273 K

<table>
<thead>
<tr>
<th>substrate</th>
<th>$E_{ox}$, V vs SCE</th>
<th>$k_{et}$, M$^{-1}$s$^{-1}$</th>
<th>$-\Delta G_{et}$, eV</th>
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<tr>
<td>TMeOB</td>
<td>1.12$^a$</td>
<td>5.4(4) $\times$ 10$^4$</td>
<td>0.24</td>
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<tr>
<td>3,4-dimethoxytoluene</td>
<td>1.33$^a$</td>
<td>1.2(1) $\times$ 10$^3$</td>
<td>0.03</td>
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<tr>
<td>1,4-dimethoxybenzene</td>
<td>1.34$^a$</td>
<td>1.0(1) $\times$ 10$^3$</td>
<td>0.02</td>
</tr>
<tr>
<td>1,3,5-trimethoxybenzene</td>
<td>1.43$^a$</td>
<td>5.5(4) $\times$ 10$^2$</td>
<td>-0.07</td>
</tr>
<tr>
<td>1,2-dimethoxybenzene</td>
<td>1.45$^a$</td>
<td>6.1(4) $\times$ 10$^1$</td>
<td>-0.09</td>
</tr>
<tr>
<td>[Fe$^{II}$(Me$_2$phen)$_3$]$^{2+}$</td>
<td>0.94$^b$</td>
<td>1.7(2) $\times$ 10$^5$ $^b$</td>
<td>0.42$^b$</td>
</tr>
<tr>
<td>[Fe$^{II}$(Ph$_2$phen)$_3$]$^{2+}$</td>
<td>1.02$^b$</td>
<td>2.1(1) $\times$ 10$^4$ $^b$</td>
<td>0.34$^b$</td>
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<td>[Fe$^{II}$(bpy)$_3$]$^{2+}$</td>
<td>1.06$^b$</td>
<td>3.6(1) $\times$ 10$^3$ $^b$</td>
<td>0.30$^b$</td>
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<td>[Fe$^{II}$(5-Clphen)$_3$]$^{2+}$</td>
<td>1.20$^b$</td>
<td>4.1(8) $\times$ 10$^2$ $^b$</td>
<td>0.16$^b$</td>
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<td>[Ru$^{II}$(bpy)$_3$]$^{2+}$</td>
<td>1.24$^b$</td>
<td>7.3(1) $\times$ 10$^1$ $^b$</td>
<td>0.12$^b$</td>
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</table>

$^a$Taken from ref 24. $^b$Taken from ref 20.
Figure S1. Absorption spectral changes observed in the oxidation of 1,2,4-trimethoxybenzene (0.25 mM) by cerium(IV) ammonium nitrate (CAN: 0.25 mM) in TFE/MeCN (v/v = 1:1) at 273 K. Absorption bands at 422 nm and 590 nm are assigned to the characteristic peaks of 1,2,4-trimethoxybenzene radical cation. The inset shows the time profile of absorbance at 422 nm due to the formation of 1,2,4-trimethoxybenzene radical cation (TMeOB⁺).
Figure S2. EPR spectra of TMeOB•⁺ produced in the oxidation of TMeOB (0.50 mM) by (a) 1 (0.50 mM) and (b) CAN (0.50 mM) in TFE/MeCN (v/v = 1:1) at 233 K. Spectra were recorded at 77 K.
Figure S3. (a) Absorption spectral changes observed in the reaction of TMeOB$^+$ (0.50 mM), which was produced by the oxidation of TMeOB (0.50 mM) by 1 (0.50 mM), with TBABr (10 mM) in TFE/MeCN (v/v = 1:1) at 273 K. The inset shows the time profile of absorbance at 422 nm due to the decay of TMeOB$^+$. (b) Absorption spectral changes observed upon addition of ScBr$_3$ (4.0 mM) to a TFE/MeCN (v/v = 1:1) solution containing 1 (0.50 mM) at 273 K. ScBr$_3$ (4.0 mM) was generated by reacting Sc(OTf)$_3$ (4.0 mM) with TBABr (15 mM) in TFE/MeCN (v/v = 1:1) at 273 K. Upon addition of ScBr$_3$ (4.0 mM) to a TFE/MeCN (v/v = 1:1) solution containing 1 (0.50 mM), blue line ($\lambda_{\text{max}} = 690$ nm) due to 1 was changed right away to red line ($\lambda_{\text{max}} = 730$ nm) due to ScBr$_3$-bound $[(\text{Bn-TPEN})\text{Mn}^{IV}(\text{O})]^2^+$ species, and then ScBr$_3$-bound $[(\text{Bn-TPEN})\text{Mn}^{IV}(\text{O})]^2^+$ species decayed. The inset shows the time profile of absorbance at 730 nm due to the decay of ScBr$_3$-bound $[(\text{Bn-TPEN})\text{Mn}^{IV}(\text{O})]^2^+$ species.
Figure S4. $^1$H NMR spectra of (a) 1,2,4-trimethoxybenzene (TMeOB, 10 mM) and (b) the reaction solution after completion of the oxidation of TMeOB (4.0 mM) by 1 (2.0 mM) in the presence of TBABr (10 mM) in TFE/MeCN ($v/v = 1:1$) at 273 K. Reaction was carried out in TFE/MeCN ($v/v = 1:1$) at 273 K. After solvent was removed by evaporation, the product was dissolved in CD$_3$CN. Benzene (1.5 mM) was used as an internal reference. Spectra were recorded in CD$_3$CN at 298 K.
Figure S5. (a) EPR spectrum of the reaction solution after completion of the oxidation of TMeOB (0.5 mM) by 1 (0.5 mM) in presence of TBABr (2.0 mM) in TFE/MeCN (v/v = 1:1) at 273 K. Inset shows EPR spectrum of [(Bn-TPEN)Mn$_{II}^{2+}$ (0.5 mM) in the presence of Sc(OTf)$_3$ (20 mM) as an authentic reference in TFE/MeCN (v/v = 1:1). (b) EPR spectrum of the reaction solution after completion of the oxidation of TMeOB (50 mM) by [(Bn-TPEN)Mn$_{II}^{2+}$ (0.5 mM) with PhIO (50 mM) in the presence of Sc(OTf)$_3$ (20 mM) and TBABr (50 mM) in TFE/MeCN (v/v = 1:1) at 273 K. Spectra were recorded at 77 K.
Figure S6. $^1$H NMR spectra of (a) 1,2,4-trimethoxybenzene (TMeOB, 10 mM) and (b) the reaction solution after completion of the oxidation of TMeOB (20 mM) by [(Bn-TPEN)Mn$^{II}$]$^{2+}$ (0.10 mM) with PhIO (10 mM) in the presence of Sc(OTf)$_3$ (20 mM) and TBABr (10 mM) in CF$_3$CD$_2$OD/CD$_3$CN (v/v 1:1) at 273 K. The peaks marked with asterisks originated from PhI, which is produced from PhIO, accompanied by generation of 1. Spectra were recorded in CF$_3$CD$_2$OD/CD$_3$CN (v/v 1:1) at 298 K. Benzene (1.5 mM) was used as an internal reference.
Figure S7. (a) Absorption spectral change observed for the generation of 1 by addition of PhIO (2.0 mM) to a TFE/MeCN (v/v = 1:1) solution containing [(BnTPEN)Mn^{II}]{2+} (0.50 mM) and Sc(OTf){3} (6.0 mM) at 273 K. (b) Absorption spectral change observed for the generation of 1 by addition of Sc(OTf){3} (6.0 mM) to a TFE/MeCN (v/v = 1:1) solution containing [(BnTPEN)Mn^{IV}(O)]{2+} (0.50 mM) at 273 K.
Figure S8. $^1$H NMR spectra of (a) 1,2,4-trimethoxybenzene (TMeOB, 10 mM) and (b, c, d, e) the reaction solutions after completion of (b) the oxidation of TMeOB (20 mM) by PhIO (10 mM) with [((Bn-TPEN)Mn$^{II}$]$^2^+$ (0.10 mM) in the presence of Sc(OTf)$_3$ (20 mM) and TBABr (10 mM), (c) the oxidation of TMeOB with PhIO in the presence of Sc(OTf)$_3$ and TBABr without [((Bn-TPEN)Mn$^{II}$]$^2^+$, (d) the oxidation of TMeOB with [((Bn-TPEN)Mn$^{II}$]$^2^+$ in the presence of Sc(OTf)$_3$ and TBABr without PhIO, and (e) the oxidation of TMeOB with [((Bn-TPEN)Mn$^{II}$]$^2^+$, PhIO and TBABr in the absence of Sc(OTf)$_3$. All reactions were carried out in TFE/MeCN (v/v = 1:1) at 273 K. After solvent was removed by evaporation, the product was dissolved in CD$_3$CN. Spectra were recorded in CD$_3$CN at 298 K. The peak marked with asterisk in (b) is for benzene (1.5 mM), which was used as an internal reference.
Figure S9. $^1$H NMR spectra of (a) 1,2,4-trimethoxybenzene (TMeOB, 10 mM) and (b) the reaction solution after completion of the oxidation of TMeOB (20 mM) by [(Bn-TPEN)Mn$^{II}$]$_2^{2+}$ (0.10 mM) with PhIO (10 mM) in the presence of Sc(OTf)$_3$ (20 mM) and TBACl (10 mM) in CF$_3$CD$_2$OD/CD$_3$CN (v/v 1:1) at 273 K. The peaks marked with asterisks originated from PhI, which is produced from PhIO, accompanied by generation of 1. Spectra were recorded in CF$_3$CD$_2$OD/CD$_3$CN (v/v 1:1) at 298 K.
Figure S10. Absorption spectral changes observed in the oxidation of 1,2-dimethoxybenzene (1.0 mM) by CAN (4.0 mM) in MeCN at 273 K.
Figure S11. Visible spectral changes observed in the photochemical reaction of 1 (0.50 mM) with benzene (500 mM) in presence of TBABr (1.0 mM) under photoirradiation (with a Xe lamp) in TFE/MeCN (v/v = 1:1) at 273 K. Inset shows time profile of absorbance at 690 nm due to the decay of 1.
Figure S12. Second-order plot of $[I]^{-1}$ vs time for the oxidation reaction of 1,2,4-trimethoxybenzene (0.50 mM) by I (0.50 mM) in TFE/MeCN (v/v = 1:1) at 273 K.
Figure S13. (a) Absorption spectral changes observed in the oxidation of 1,3,5-trimethoxybenzene (2.5 mM) by 1 (0.25 mM) in TFE/MeCN (v/v = 1:1) at 273 K. The inset shows the time profile of the absorbance at 500 nm due to the formation 1,3,5-trimethoxybenzene radical cation. (b) Plot of $k_{obs}$ vs concentration of 1,3,5-trimethoxybenzene.
Figure S14. (a) Absorption spectral changes observed in the oxidation of 1-methyl-3,4-dimethoxybenzene (2.5 mM) by 1 (0.25 mM) in TFE/MeCN (v/v = 1:1) at 273 K. The inset shows the time profile of the absorbance at 420 nm due to the formation of 1-methyl-3,4-dimethoxybenzene radical cation. (b) Plot of $k_{obs}$ vs concentration of 1-methyl-3,4-dimethoxybenzene.
Figure S15. (a) Absorption spectral changes observed in the oxidation of 1,4-dimethoxybenzene (5.0 mM) by 1 (0.25 mM) in TFE/MeCN (v/v = 1:1) at 273 K. The inset shows the time profile of the absorbance at 430 nm due to the formation 1,4-dimethoxybenzene radical cation. (b) Plot of $k_{obs}$ vs concentration of 1,4-dimethoxybenzene.
Figure S16. (a) Absorption spectral changes observed in the oxidation of 1,2-dimethoxybenzene (5.0 mM) by 1 (0.25 mM) in TFE/MeCN (v/v = 1:1) at 273 K. The inset shows the time profile of the absorbance at 622 nm due to the formation of 1,2-dimethoxybenzene radical cation. (b) Plot of $k_{ob}$ vs concentration of 1,2-dimethoxybenzene.
Figure S17. Plot of $\Delta H_{msl}$ vs concentration of TMeOB determined by simulation of the EPR spectra of TMeOB$^{\bullet+}$ (0.25 mM) in the presence of various concentrations of TMeOB (0 – 1.5 mM) in TFE/MeCN (v/v = 1:1) at 233 K. $\Delta H_{msl}$ is the maximum slope linewidth of the EPR spectra in the presence of the neutral species.
Figure S18. Absorption spectral changes observed in the oxidation of TMeOB (0.25 mM) by 1 (0.25 mM) in the presence of TBABr (10 mM) in TFE/MeCN (v/v = 1:1) at 273 K. It should be noted that no formation of TMeOB•+ was observed in this reaction, indicating that ET from TMeOB to 1 is the rate-determining step.
References


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