Angewandte Chemie

Eine Zeitschrift der Gesellschaft Deutscher Chemiker

Supporting Information

69451 Weinheim, Germany

Supporting Information for *Angew. Chem. Int. Ed.*

Ruthenium Porphyrin-Catalyzed Aerobic Oxidation of Terminal Aryl Alkenes to Aldehydes by Tandem Epoxidation-Isomerization Pathway

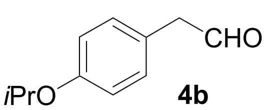
*Gaoxi Jiang, Jian Chen, Hung-Yat Thu, Jie-Sheng Huang, Nianyong Zhu, and Chi-Ming Che**

General: Unless otherwise indicated, all reactions were performed in air and all the solvents were dried and freshly distilled. Substrates **3a**, **3c**, and **3f–3n** were purchased from Aldrich or Acros and were used as received. Substrates **3b**,[1] **3d**,[2] and **3e**,[3] catalysts **1a**,[4] **1b**,[4] and **2a**[5] and bis-pocket porphyrin H_2tmttp[6] were prepared according to literature methods. ^{1}H NMR spectra were recorded in $CDCl_3$ solutions on a Bruker AM300 or AV400 spectrometer at room temperature (the chemical shifts are relative to tetramethylsilane). UV/Vis spectra were obtained on a Hewlett-Packard 8453 diode array spectrophotometer interfaced with an IBM compatible PC. Infrared spectra were measured on a Bio-Rad FTS-185 spectrophotometer (KBr disk). EI mass spectra were obtained on an HP5989A spectrometer. FAB and ESI mass spectra were collected on a Finnigan MAT 95 and a Finnigan LCQ quadrupole ion trap mass spectrometer, respectively.

Preparation of [Ru^{II}(tmttp)(CO)(H$_2$O)]: This complex was prepared from the reaction of $Ru_3(CO)_{12}$ with H_2tmttp in decalin by the same procedure as that for other carbonylruthenium(II) porphyrin analogues.[7] Yield: 90%; ^{1}H NMR (400 MHz, $CDCl_3$): δ_H 8.99 (s, 4H), 7.79–7.72 (m, 12H), 7.16–7.08 (m, 16H), 6.56 (t, $J = 7.2$ Hz, 4H), 6.51–6.46 (m, 20H), 2.74 (s, 12 H); UV/Vis (CH_2Cl_2): λ_{max}/nm (log ε) 410 (5.27), 527 (4.08), 560 (4.32); IR: 1938 cm^{-1} [ν(CO)]; FAB MS: m/z 1407 $[M - H_2O]^+$, 1379 $[M - H_2O - CO]^+$.

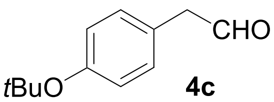
Preparation of [Ru^{VI}(tmttp)O$_2$] (2c): This complex was prepared from the oxidation of [Ru^{II}(tmttp)(CO)(H_2O)] with *m*-chloroperbenzoic acid by the same procedure as that for other dioxoruthenium(VI) porphyrin analogues.[8] Yield: 67%. The spectral data are given in ref. [16] in text.

Typical procedure for the formation of 4a–4n by aerobic oxidation of 3a–3n catalyzed by 1a: Alkene substrate **3** (0.10 mmol), **1a** (1.9 mg, 2 mol%), and trimethyl(phenyl)silane ($PhSiMe_3$, 1.5 mg, 0.01 mmol, internal standard) were dissolved in $CDCl_3$ (1.0 mL) in a tube at room temperature. An aqueous solution containing $NaHCO_3$ (0.34 mg, 4 mol%) and water (0.3 mL) was added. The biphase solution was stirred, and the progress of the reaction was monitored by TLC and ^{1}H NMR spectroscopy. After completion of the reaction, the yield of the aldehyde product (based on the amount of starting substrate) was determined by ^{1}H NMR spectroscopy. In some cases, the aldehyde product was isolated through separation of the reaction mixture by flash chromatography on a silica gel column. The spectral data for aldehydes **4b** and **4c** are given in the following.



4b

^{1}H NMR (300 MHz, $CDCl_3$): δ 9.72 (t, J = 2.5 Hz, 1H), 7.12 (d, J = 8.7 Hz, 2H), 6.87 (d, J = 8.6 Hz, 2H), 4.54 (m, 1H), 3.62 (d, J = 2.4 Hz, 2H), 1.33 (d, J = 6.1 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 199.70, 157.30, 130.65, 123.46, 116.37, 69.95, 49.72, 22.01; IR (cm^{-1}): 3033, 2978, 2934, 2725, 1724, 1612, 1510, 1385, 1373, 1244, 1121, 955, 830; HRMS: *m*/*z* Calcd for $C_{11}H_{14}O_2$: 178.0994, found: 178.0993.



4c

^{1}H NMR (300 MHz, $CDCl_3$): δ 9.68 (t, J = 2.4 Hz, 1H), 7.07 (d, J = 8.5 Hz, 2H), 6.96 (d, J = 8.5 Hz, 2H), 3.59 (d, J = 2.3 Hz, 2H), 1.31 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 199.44, 154.75, 130.06, 126.52, 124.52, 78.48, 49.80, 28.79; IR (cm^{-1}): 3032, 2979, 2934, 2725, 1726, 1608, 1506, 1391, 1367, 1239, 1162, 896, 853; HRMS: *m*/*z* Calcd for $C_{12}H_{16}O_2$: 192.1150, found: 192.1142.

For the characterization of aldehydes **4a**,[9] **4d**,[10] **4e**,[11] **4f**,[12] **4g**,[13] **4h**,[14] **4i**,[15] **4j**,[16] **4k**,[17] **4l**,[18] **4m**,[19] **4n**,[20] see the corresponding references in the literature.

Preparation of 5 through 1a-catalyzed aerobic oxidation of 3: A mixture of **3a** (109.2 mg, 0.8 mmol) or **3e** (210.3 mg, 1.0 mmol), **1a** (3 mol%), $CHCl_3$ (10 mL), and aqueous solution of $NaHCO_3$ (10 mol% for **3a**, 6 mol% for **3e**) in a 50-mL flask was stirred under O_2 (using a balloon) at room temperature for 5 h. The solvent was removed under reduced pressure, followed by addition of Ph_3P (1.2 equiv.), toluene (10 mL), and EDA (1.2 equiv.). The mixture was heated at 80 °C for 2 h, and then cooled to room temperature. After removal of the solvent, the residue was separated by flash chromatography on a silica gel column with petroleum ether/ethyl acetate (10:1 v/v) as eluent to afford **5a**[21] (127.1 mg, 71% yield) or **5b**[22] (216.0 mg, 73% yield).

Catalytic aerobic oxidation of 3a to 4a in the presence of $NaHCO_3$ dissolved in H_2O^{18}: A mixture of **3a** (134.2 mg, 1 mmol), **1a** (19.0 mg, 2 mol%), anhydrous $NaHCO_3$ (3.4 mg, 4 mol%), H_2O^{18} (95% O^{18}, 0.5 mL), and $CHCl_3$ (3 mL) open to air was stirred at room temperature. The reaction was monitored by ^1H NMR spectroscopy until $[Ru^{II}(tmp)(CO)]$ was the only observable ruthenium porphyrin species. The aldehyde product isolated was analyzed by high resolution mass spectrometry, revealing that ~72% of the aldehyde contained O^{18}.

Procedure for the time course measurements: A solution of **3f** (13.4 mg, 0.1 mmol), **1a** (1.8 mg, 1.9 mol%), and trimethyl(phenyl)silane ($PhSiMe_3$, 1.5 mg, 0.01 mmol, internal standard) in $CDCl_3$ (1 mL) was mixed with a solution of $NaHCO_3$ (0.34 mg, 4 mol%) in H_2O (0.3 mL). The mixture was stirred at room temperature. The ^1H NMR spectrum of the mixture was measured at 4 min intervals before t = 0.5 h and subsequently at 0.5 h intervals until the reaction was completed (t = 5.5 h). An additional amount of **1a** (0.1 mg, 0.1 mol%) was then introduced and the ^1H NMR spectrum of the reaction mixture was measured at 0.5 h intervals.

Effect of dioxygen pressure on the yield of 4a for 1a-catalyzed oxidation of 3a with dioxygen: A mixture of **3a** (13.4 mg, 0.1 mmol), **1a** (0.48 mg, 0.5 mol%), $NaHCO_3$ (0.25 mg, 3 mol%), $CDCl_3$ (1 mL), and H_2O (0.3 mL) under O_2 was stirred at room temperature for 6 h. The yield of resulting **4a** (based on the amount of starting **3a** and determined by ^1H NMR with $PhSiMe_3$ as internal standard) was 25%, 27%, and 25% for O_2 pressures of 3, 5, and 7 atm, respectively.

Procedure for the isomerization of styrene oxide to phenylacetaldehyde catalyzed by 1a or 2a: A mixture of styrene oxide (12.0 mg, 0.1 mmol) and catalyst (2 mol%)

in $CDCl_3$ (1 mL) was heated at 50 °C. The reaction was monitored by ^1H NMR spectroscopy until no more aldehyde was formed. The yield of the aldehyde product was determined by ^1H NMR with $PhSiMe_3$ as internal standard.

Procedure for the formation of 4a, 4g, 4h, 4j, 4k by oxidation of 3a, 3g, 3h, 3j, 3k, respectively, with dioxygen catalyzed by 2c: Alkene substrate **3** (0.10 mmol), **2c** (0.28 mg, 0.2 mol%), and $PhSiMe_3$ (1.5 mg, 0.01 mmol, internal standard) were dissolved in $CDCl_3$ (1.0 mL) in a vial at room temperature. The mixture was stirred at 60 °C under O_2 and the progress of the reaction was monitored by ^1H NMR spectroscopy. After completion of the reaction (reaction time: 7 h for **3a**, **3g**, **3h**; 12 h for **3j**, **3k**), the yield of the aldehyde product (based on the amount of starting substrate) was determined, by ^1H NMR spectroscopy, to be 79.2%, 75.4%, 73.6%, 48.6%, 64.0% for **4a**, **4g**, **4h**, **4j**, **4k**, respectively.

Catalyst recycling for the oxidation of 3a to 4a with dioxygen catalyzed by 2a or 2c: After completion of a reaction run with a catalyst loading of 2 mol% for **2a** (1.8 mg) or 0.5 mol% for **2c** (0.71 mg), a solution of *m*-CPBA (5 equiv. to the catalyst) in $CDCl_3$ (0.1 mL) was added to the reaction mixture, resulting in the formation of **2a** or **2c**, as indicated by ^1H NMR and UV/Vis spectroscopy. Substrate **3a** (13.4 mg, 0.1 mmol) was then added, and the reaction mixture was stirred under dioxygen at room temperature for the **2a**-catalyzed reaction and at 60 °C for the **2c**-catalyzed reaction. After completion of the reaction, the yields of **4a** (based on the amount of starting **3a**) were determined by ^1H NMR spectroscopy. Control experiments using 20 mol% *m*-CPBA in the absence of catalyst **2a** or **2c** under the same conditions revealed the formation of **4a** in <1% yield.

X-ray crystal structure determination of $[Ru^{II}(tmttp)(CO)(H_2O)]\cdot 2MeOH$: A diffraction-quality crystal ($0.4 \times 0.15 \times 0.1$ mm^3), obtained by layering methanol on the top of a chloroform solution at room temperature, was mounted in a glass capillary for data collection at 28 °C on a MAR diffractometer with a 300 mm image plate detector using graphite monochromatized Mo-K_α radiation ($\lambda = 0.71073$ Å) (oscillation step of φ: 1.5°, exposure time: 10 min, scanner distance: 120 mm; images collected: 130). The images were interpreted and the intensities were integrated using program DENZO.[23] The structure was solved by direct methods employing SIR-97[24] program on PC. Ru and many other non-H atoms were located according to the direct methods and the successive least-square Fourier cycles. The positions of other non-hydrogen atoms were found after successful refinement by full-matrix least-squares using program SHELXL-97[25] on PC. There was half of formula unit in the asymmetric unit. Ru1 is slightly deviated from the special position (0, 0, 0) and has to be refined isotropically. When Ru1 was refined anisotropically, it became non-positive definite gradually, and a worse *R*-index was found. The axial positions were occupied by carbonyl and water. One crystallographic asymmetric unit consists of half of formula unit, together with two halves of methanol (the half occupancies of the methanol groups were checked by free refinement of the occupancies, and these correspond to the occupancies of the axial groups). In the final stage of least-squares refinement, Ru, the non-hydrogen atoms of axial ligands, and methanol molecules were refined isotropically, other non-H atoms were refined anisotropically. H atoms (except those on methanol and water O) were generated by program SHELXL-97. The positions of H atoms were calculated based on riding mode with thermal parameters equal to 1.2 times that of the associated C atoms, and participated in the calculation of final *R*-indices. The crystal data and structure refinement are summarized in Table S2.

References

[1] S. K. Talluri, A. Sudalai, *Org. Lett.* **2005**, *7*, 855–857.

[2] G. D. Cuny, J. Cao, J. R. Hauske, *Tetrahedron Lett.* **1997**, *38*, 5237–5240.

[3] R. A. Fernandes, M. S. Bodas, P. Kumar, *Tetrahedron* **2002**, *58*, 1223–1227.

[4] W.-H. Leung, T. S.-M. Hun, H.-W. Hou, K.-Y. Wong, *J. Chem. Soc. Dalton Trans.* **1997**, 237–244.

[5] J. T. Groves, R. Quinn, *Inorg. Chem.* **1984**, *23*, 3844–3846.

[6] N. Bag, S. S. Chern, S.-M. Peng, C.-K. Chang, *Tetrahedron Lett.* **1995**, *36*, 6409–6412.

[7] D. P. Rillema, J. K. Nagle, L. F. Barringer Jr., T. J. Meyer, *J. Am. Chem. Soc.* **1981**, *103*, 56–62.

[8] a) J. T. Groves, R. Quinn, *Inorg. Chem.* **1984**, *23*, 3844–3846; b) C.-M. Che, J.-L. Zhang, R. Zhang, J.-S. Huang, T.-S. Lai, W.-M. Tsui, X.-G. Zhou, Z.-Y. Zhou, N. Zhu, C. K. Chang, *Chem. Eur. J.* **2005**, *11*, 7040–7053.

[9] J. Svoboda, Z. Kocfeldova, J. Palecek, *Collect. Czech. Chem. Commun.* **1988**, *53*, 822–832.

[10] G. D. Cuny, J. Cao, J. R. Hauske, *Tetrahedron Lett.* **1997**, *38,* 5237–5240.

[11] R. A. Fernandes, M. S. Bodas, P. Kumar, *Tetrahedron* **2002**, *58*, 1223–1227.

[12] N. Miyaura, K. Maeda, H. Suginome, *J. Org. Chem.* **1982**, *47*, 2117–2120.

[13] H. Chikashita, Y. Morita, K. Itoh, *Synth. Commun.* **1987**, *17*, 677–684.

[14] J. A. Wright, M. J. Gaunt, J. B. Spencer, *Chem. Eur. J.* **2006**, *12*, 949–955.

[15] G. Motsios, M. Ahmar, A.-I. Nadi, J. Paris, *Synth. Commun.* **1991**, *21*, 819–826.

[16] W. L. Bao, Q. Wang, Y. F. Zheng, *Chi. Chem. Lett.* **2004**, *15*, 1029–1032.

[17] M. Solinas, J. Jiang, O. Stelzer, W. Leitner, *Angew. Chem. Int. Ed.* **2005**, *44*, 2291–2295.

[18] H. Kikuchi, K. Kogurre, M. Toyoda, *Chem. Lett*. **1984**, 341–344.

[19] I. O. Donker, H. Li, S. F. Queener, *Eur. J. Med. Chem.* **2003**, *38*, 605–611.

[20] G. Parrinello, J. K. Stille, *J. Am. Chem. Soc.* **1987**, *109*, 7122–7127.

[21] H. S. Outram, S. A. Raw, R. J. K. Taylor, *Tetrahedron Lett.* **2002**, *43*, 6185–6187.

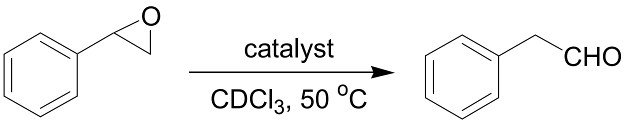
[22] R. A. Fernandes, M. S. Bodas, P. Kumar, *Tetrahedron* **2002**, *58*, 1223–1227.

[23] Z. Otwinowski, W. Minor, in *Methods in Enzymology*, *Vol. 276: Macromolecular Crystallography*, part A, (Eds.: C. W. Carter, Jr., R. M. Sweet), Academic Press, New York, **1997**, pp. 307–326.

[24] A. Altomare, M. C. Burla, M. Camalli, G. Cascarano, C. Giacovazzo, A. Guagliardi, A. G. G. Moliterni, G. Polidori, R. Spagna, *J. Appl. Cryst.* **1999**, *32*, 115–119.

[25] G. M. Sheldrick, *SHELX97. Programs for Crystal Structure Analysis* (Release 97-2). University of Götingen, Germany.

Table S1. Isomerization of styrene oxide to phenylacetaldehyde catalyzed by **1a** and **2a**[a]

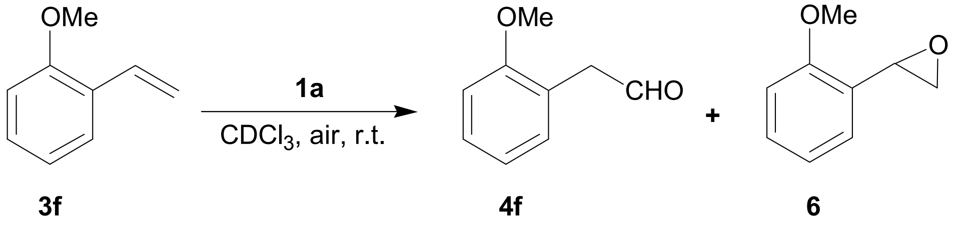


Entry	Catalyst	Time [h]	Yield [%][b]
1	**1a**	6	>98
2	**2a**	3	62
3	[Ru^{II}(tmp)(CO)]	6	0

[a] Reaction conditions: styrene oxide (0.1 mmol), catalyst (2 mol%), $CDCl_3$ (1 mL), open to air. [b] Determined by ^1H NMR.

Table S2. Crystal data and structure refinement for [$\mathrm{Ru^{II}}$(tmttp)(CO)(H_2O)]·2MeOH

formula	$C_{99}H_{74}N_4O_4Ru$
FW	1484.69
color	purple
crystal size [mm^3]	0.40 × 0.15 × 0.10
crystal system	monoclinic
space group	$P\ 2_1/c$
a [Å]	13.481(2)
b [Å]	26.109(4)
c [Å]	11.810(2)
α [°]	90
β [°]	93.88(3)
γ [°]	90
V [$Å^3$]	4147.3(11)
Z	2
D_c [g cm^{-3}]	1.189
μ [mm^{-1}]	0.243
F(000)	1544
$2\theta_{max}$ [°]	51.34
no. unique data	7369
GoF	0.84
R1	0.060
wR2	0.159
largest diff peak/hole [e $Å^{-3}$]	0.796/–0.786



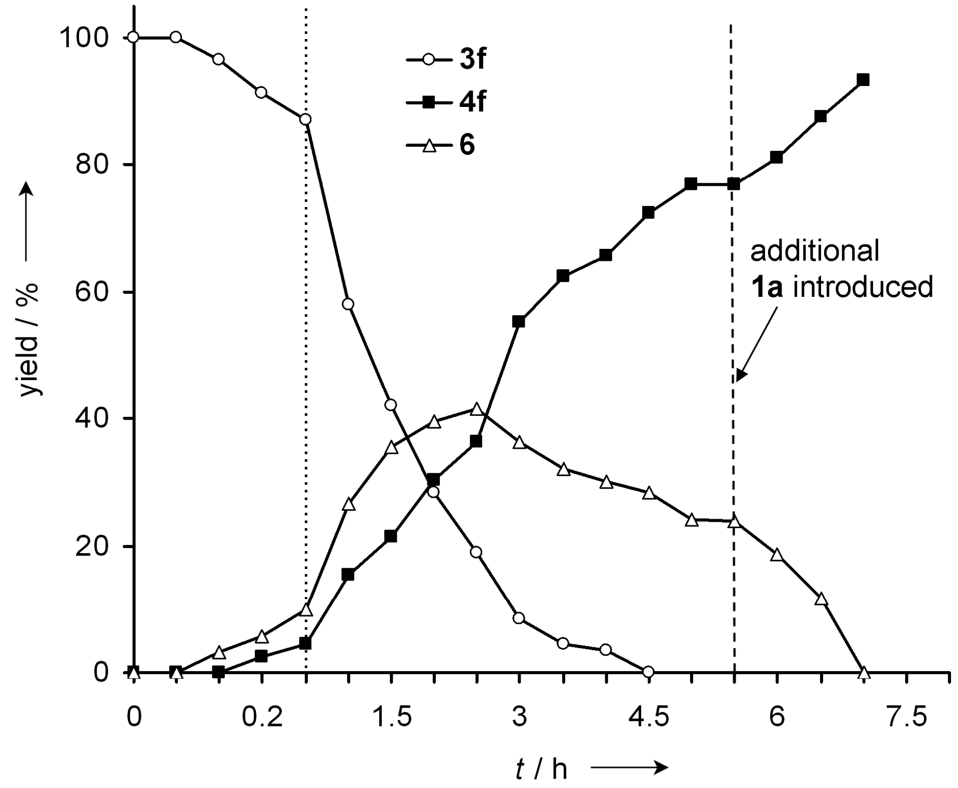


Figure S1. Time course plot for the aerobic oxidation of **3f** in $CDCl_3$ catalyzed by **1a** in the presence of $NaHCO_3$ (4 mol%) and H_2O (0.3 mL) at room temperature (the dotted line indicates a change in the time scale). This catalytic process (**1a**: 1.9 mol%) exhibited an induction period of about 4 min, during which the catalyst **1a** remained unchanged. After that, **2a** was formed in the mixture (identified from the ^1H NMR spectrum), and the oxidation of **3f** started, affording a mixture of aldehyde **4f** and epoxide **6** with the latter in a larger amount. The amount of both **4f** and **6** increased with time (t) until $t = 2.5$ h. Then, the amount of **4f** kept increasing whereas that of **6** became decreasing with time. At $t = 5$ h the reaction mixture contained [Ru^{II}(tmp)(CO)] but neither **1a** nor **2a**. From $t = 5$ h to 5.5 h, no change in the amounts of **4f** and **6** was observed. Addition of 0.1 mol% **1a** to the reaction mixture at this stage initiated a further drop of the amount of **6** with time, with concomitant increase in the amount of **4f**. At $t = 7$ h, **6** was completely consumed. These observations suggest that **2a** is an intermediate in the catalytic process and **1a** can catalyze the conversion of **6** into **4f**, whereas the carbonyl complex [Ru^{II}(tmp)(CO)] has no activity toward the catalytic aldehyde formation.