

Aerobic enantioselective alkene epoxidation by a chiral *trans*-dioxo(*D*₄-porphyrinato)ruthenium(VI) complex

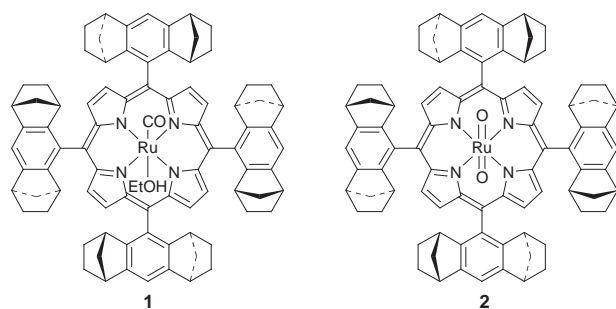
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A dioxoruthenium(VI) complex with a *D*₄-chiral porphyrin ligand has been prepared and characterized by spectroscopic methods and X-ray crystal analysis; the complex exhibits catalytic activity towards aerobic enantioselective epoxidation of prochiral alkenes with enantioselectivity up to 73% ee at an oxygen pressure of 8 atm.

Among various terminal oxidants used in metalloporphyrin-catalysed organic oxidations,¹ dioxygen is the most appealing since it is both economical and environmental friendly,^{2,3} but reports on the use of dioxygen in enantioselective alkene epoxidations are sparse. Chiral Mn(β -ketoiminato) complexes were reported to catalyse asymmetric aerobic alkene epoxidations but aldehyde is required as a sacrificial reducing agent.⁴ We herein report the first example of aerobic enantioselective epoxidation of alkenes that does not rely on the use of a co-reductant. The *D*₄-porphyrin was synthesized according to the literature procedure.⁵ The catalyst precursor is [Ru^{III}(por^{*})(CO)(EtOH)] **1**,^{6,7} which has been characterized by X-ray crystallography.⁷ Oxidation of complex **1** with



m-chloroperoxybenzoic acid in CH₂Cl₂ afforded [Ru^{VI}(por^{*})O₂] **2** in 60–70% yield after purification by column chromatography.‡ Complex **2** is diamagnetic. Its FAB spectrum shows peaks attributed to M⁺, [M⁺ – O] and [M⁺ – 2O]. The $\nu_{\text{as}}(\text{RuO}_2)$ stretch and the oxidation marker band are positioned at 822 and 1019 cm⁻¹ respectively. These spectroscopic data agree with the *trans*-dioxoruthenium(VI) formulation.^{8,9} The structure with a high *R*_w value was established by an X-ray diffraction study (Fig. 1).§ The Ru=O distances average 1.74 Å, as expected for a Ru=O bond.¹⁰ Unlike other reported [Ru^{VI}(por)O₂] (por = porphyrinato dianion) complexes,^{2,8,9} complex **2** is stable in solid state for months and in purified MeCN or CH₂Cl₂ for more than 24 h. However in the presence of pyrazole, it reacts with alkenes to give the corresponding epoxides with moderate to good enantioselectivities and a paramagnetic ruthenium product that was formulated to be [Ru^{IV}(por^{*})(pz)₂] [pz = pyrazolate, $\mu_{\text{eff}} = 2.94 \mu_{\text{B}}$ (solid sample) at room temp., FABMS *m/z* = 1375] (Scheme 1). The results are summarized in Table 1. For the five alkenes studied, the ee ranged from 20 to 72%. The 65% ee of styrene oxide (entry 1) is among the highest obtained with chiral porphyrin catalysts.^{11,12} However, the ee obtained for *cis*-disubstituted alkenes are not as high as those obtained with chiral Mn–Schiff

base catalytic system.¹³ The absolute configurations of the major enantiomers of styrene oxide and *cis*- β -methylstyrene oxide were determined to be (*R*) and (1*R*, 2*S*) respectively. The epoxidation of *cis*- β -methylstyrene (entry 2) proceeded with high retention of configuration. Epoxidation of *trans*- β -methylstyrene gave only 20% ee and complete retention of configuration (entry 3).

Interestingly, the dioxoruthenium complex catalysed enantioselective aerobic oxidation of alkenes with moderate to good ee (Scheme 2). The results are listed in Table 1. Catalytic oxygenation of styrene using air at 1 atm pressure in CH₂Cl₂ gave very low turnover. However, under 8 atm pressure of oxygen, styrene oxide was obtained with 10 turnovers and 70% ee (entry 1). With *cis*- β -methylstyrene as the substrate, *cis*- β -methylstyrene oxide was observed with 20 turnovers and 69% ee and the ee increased to 73% if toluene was used as the solvent. The *cis/trans* ratio was 10 (entry 2), a value similar to that obtained in the stoichiometric reaction. Prolonged reaction time from one to two days did not increase the total turnovers. At the end of the reaction, UV–VIS spectrophotometric analysis of the reaction mixture revealed that the ruthenium–porphyrinato moiety remained intact (Soret band was at 411 nm). A brown diamagnetic complex, which showed no $\nu(\text{C}=\text{O})$ IR band, was isolated after silica gel-column chromatography using ethyl acetate as the eluent. Its FABMS spectrum revealed

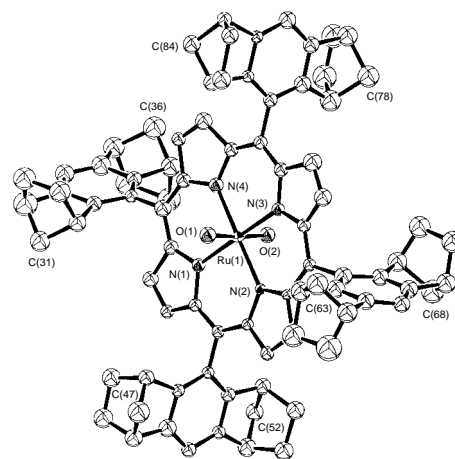
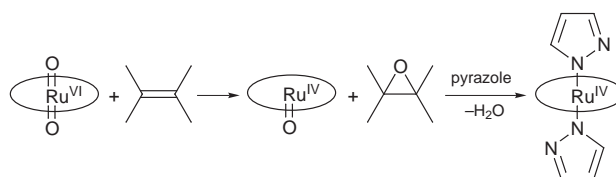

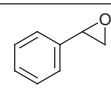

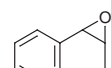
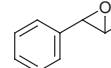

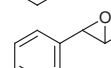
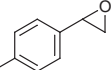

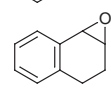


Fig. 1 Perspective drawing of **2**. Selected bond lengths (Å) and angles (°): Ru–O(1) 1.73(1), Ru–O(2) 1.75(1), Ru–N(1) 2.08(1), Ru–N(2) 2.069(10), Ru–N(3) 2.05(1), Ru–N(4) 2.05(1); O(1)–Ru–O(2) 175.4(5), O(1)–Ru–N(1) 91.1(5), N(1)–Ru–N(2) 90.3(4), N(1)–Ru–N(3) 178.3(5).

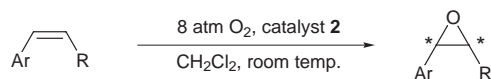


Scheme 1

Table 1 Enantioselective epoxidation of alkenes by [Ru^{VI}(por*)O₂]

Entry	Substrate	Product	Stoichiometric ^a		Catalytic aerobic ^b	
			% yield ^c	% ee ^d	turnover no. ^e	% ee ^d
1			61 ^f	65 (R) ^{f,g}	10	70 (R)
		benzaldehyde	22		5	
		2-phenylacetaldehyde	13		1	
2			64	72 (1R, 2S) ^h	20	69 (1R, 2S)
			5	n.d.	2	n.d.
3			66 ^f	20 ^f	—	—
			71	45 (R) ^j	11	52 (R)
5			61	71	14	56

^a Stoichiometric reactions were conducted at room temperature for 12 h; oxidant 4 mg, substrate 200 mg, pyrazole 50 mg in 5 ml CH₂Cl₂ unless otherwise stated. ^b Reactions were performed at room temp. at ca. 8 atm for 22–24 h; catalyst 4 mg and substrate 40 mg in 4 ml CH₂Cl₂ unless otherwise stated. ^c Yield were calculated based on the amount of ruthenium complex. ^d Enantiomeric excesses were determined by chiral GC (J&W Scientific Cyclodex B; length 30 m for entries 1, 2, 4 and 5, chiraldex G-TA, 30 m for entry 3). ^e The product yields for the calculation of turnover no. were determined by GC with *p*-dichlorobenzene or *p*-bromochlorobenzene as internal standards. ^f In benzene. ^g Absolute configuration was determined by comparison with an authentic sample. ^h Absolute configuration was determined by matching the order of elution of the two enantiomers on a Cyclodex-B column. ⁱ In toluene. ^j Absolute configuration was determined by comparing its ¹H NMR spectrum in the presence of Eu(hfc)₃ with that of a sample of known enantiomeric composition, J. T. Groves and R. S. Myres, *J. Am. Chem. Soc.*, 1983, **105**, 5791.

**Scheme 2**

a [Ru(por*)(C₉H₁₀O)] ion peak [*m/z* = 1377 (20%)]. The dioxoruthenium(vi) complex is likely to be the active intermediate of the reaction, since with the exception of 1,2-dihydronaphthalene, both the catalytic and stoichiometric reactions produced similar ee for the same substrate, and thus the mechanism of this reaction could be similar to that of the [Ru(tmp)O₂] (H₂tmp = tetramesitylporphyrin) system reported by Groves and Quinn.² As the Ru-*D*₄-porphyrin moiety has survived the oxidation, we envisage that high catalytic turnovers can be achieved through optimizing the reaction conditions. Thus this work has provided a starting point for designing

future catalysts for efficient aerobic enantioselective epoxidation without the need of a sacrificial reducing agent.

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Notes and References

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‡ ¹H NMR (300 MHz, CDCl₃), δ 0.8–2.4 (m), 2.58 (s, 8 H), 3.80 (s, 8 H), 7.44 (m, 4 H, ArH), 8.73 (s, 8 H, pyrrolic H). ¹³C NMR (300 MHz, CDCl₃), δ 27.183, 27.565, 42.417, 44.403, 49.339, 113.988, 118.923, 127.908, 130.780, 141.533, 144.272, 148.062. FABMS+: *m/z* 1274 (M⁺, 35%), 1258 (M⁺ – O, 23%), 1242 (M⁺ – 2O, 98%).

§ *Crystallographic data for 2*: [Ru(por*)O₂]-3MeCN): C₉₀H₈₅N₇O₂Ru, *M* = 1397.78, monoclinic, space group *P*2₁ (no. 4), *a* = 14.734(2), *b* = 18.447(3), *c* = 15.627(3) Å, β = 110.61(2)°, *U* = 3975(1) Å³, *Z* = 2, *D*_c = 1.170 g cm⁻³, *F*(000) = 1468, μ = 2.48 cm⁻¹, crystal dimensions 0.10 × 0.05 × 0.30 mm. Diffraction data were collected at 28 °C on a MAR diffractometer with a 300 mm image plate detector using graphite monochromated Mo-Kα radiation (λ = 0.710 73 Å). The images were interpreted and intensities integrated using program DENZO. 3692 Unique and independent reflections were obtained, 3048 with *I* > 3σ(*I*) were used in the structural analysis. These reflections were in the range *h* 0–13, *k* 0–17, *l* –15 to 15 with 2θ_{max} = 51.2°. The structure was solved by Patterson methods and expanded by Fourier methods (PATY) and refinement by full-matrix least squares using the software package TeXsan on a Silicon Graphics Indy computer. In the least-squares refinement, in view of the large thermal parameters of the four chiral radical C₁₆H₁₇, only the Ru atom was refined anisotropically and all the other 99 non-H atoms were refined isotropically and 88 H atoms at calculated positions with thermal parameters equal to 1.3 times that of the attached C atoms were not refined. Convergence for 405 variable parameters by least-squares refinement on *F* with *w* = 4*F*_o²/σ²(*F*_o²), where σ²(*F*_o²) = [σ²(*I*) + (0.063*F*_o²)²] for 3048 reflections with *I* > 3σ(*I*) was reached at *R* = 0.084 and *wR* = 0.117 with a goodness-of-fit of 3.00, (Δ/σ)_{max} = 0.04 for atoms of the porphyrin skeleton. The final difference Fourier map had maximum positive and negative peaks of 1.15 and 0.51 e Å⁻³ respectively. CCDC 182/892.

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