Applied Catalysis A: General 478 (2014) 275–282

Contents lists available at ScienceDirect

Applied Catalysis A: General

journal homepage: www.elsevier.com/locate/apcata

Visible light-promoted selective oxidation of sulfides to sulfoxides catalyzed by ruthenium porphyrins with iodobenzene diacetate

Tse-Hong Chen, Zhibo Yuan, Aaron Carver, Rui Zhang*

Department of Chemistry, Western Kentucky University, 1906 College Heights Blvd no. 11079, Bowling Green, KY 42101, USA

ARTICLE INFO

Article history:
Received 18 December 2013
Received in revised form 3 April 2014
Accepted 5 April 2014
Available online 15 April 2014

Keywords:
Ruthenium porphyrin
Oxidation
Sulfide
Iodobenzene diacetate
Visible light

ABSTRACT

Under visible light irradiation, the carbonyl ruthenium(II) porphyrin complexes efficiently catalyze the selective oxidation of sulfides to sulfoxides with iodobenzene diacetate [PhI(OAc)$_2$] as the oxygen source. Various thioanisoles and allylic sulfides were oxidized to the corresponding sulfoxides without overoxidation to sulfones. The high selectivity of this unprecedented oxygen-transfer process is mechanistically rationalized by a low-reactivity ruthenium(IV)-oxo species which can be detected in the reaction of carbonyl ruthenium(II) porphyrin with iodobenzene diacetate. To the best of our knowledge, this is the first demonstration of a mild and high-yield method for the highly selective sulfoxidations by ruthenium porphyrins and PhI(OAc)$_2$.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

The selective oxidation of sulfides to sulfoxides (sulfoxidation) is of great importance in organic synthesis [1]. Organic sulfoxides are valuable synthetic reagents for the production of a variety of chemically and biologically significant molecules. Optically active sulfoxides are also useful intermediates in medicinal and pharmaceutical chemistry to prepare the therapeutic agents such as antiulcer (proton pump inhibitors), antibacterial, antifungal, antiatherosclerotic, antihypertensive and cardiotonic agents, as well as psychotonics and vasodilators [2]. A large variety of electrophilic reagents such as peracids, hydrogen peroxide, hypochlorite, sodium periodate, iodosobenzene, peroxyacids, and highly toxic oxo metal oxidants have been utilized for the oxidation of conventional sulfides with the aim of obtaining high selectivity for sulfoxide over sulfone [3,4]. However, the methods that are currently reported rarely provide the ideal combination of selectivity, fast reaction kinetics, and high product yields. The search for the efficient and selective catalytic oxidation reactions for the sulfoxide preparation has continued to be the interest of chemical research.

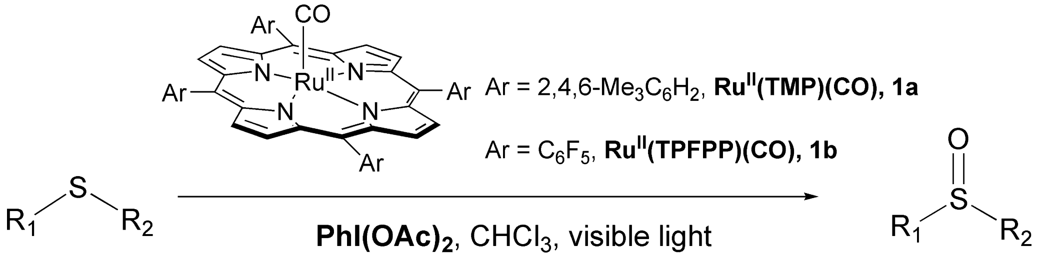
In the past decades, many transition metal complexes [5] have been synthesized to mimic the predominant oxidation catalysts in Nature, namely the cytochrome P450 enzymes [6]. In biomimetic catalytic oxidations, a transition metal catalyst is oxidized to a high-valent metal-oxo species [7] by a sacrificial oxidant, and then the reactive transition metal-oxo intermediate oxidizes the substrate [8]. In this regard, ruthenium porphyrin complexes are among the most extensively studied biomimetic oxidation catalysts in view of their rich coordination and redox chemistry [9,10]. Ruthenium porphyrins can be used to catalyze the oxidation of a wide variety of organic substrates, particularly for various alkenes, benzylic hydrocarbons and arenes [11]. Product turnovers of over 10,000 can be reached by recycling the catalysts several times or by performing the oxidation at low catalyst loadings, as demonstrated in a number of selected cases [12,13]. The synthetic ruthenium porphyrins associated with various sacrificial oxidants such as iodosobenzene (PhIO), *tert*-butyl hydroperoxide (TBHP) and *m*-chloroperoxybenzoic acid (*m*-CPBA) can catalyze a wide variety of oxidation reactions including epoxidation, hydroxylation and oxidation of amines, sulfides, alcohols and aldehydes [11,14]. In particular, with heteroaromatic *N*-oxides as oxygen source, ruthenium porphyrin complexes exhibit high region-, chemo- and stereoselectivity in the catalytic oxidation of a variety of hydrocarbons [13,15,16]. Notably, the well-characterized *trans*-dioxoruthenium(VI) porphyrins, formulated as [$\text{Ru}^{\text{VI}}(\text{Por})\text{O}_2$], have been shown to catalyze the clean aerobic epoxidation of olefins in the absence of a reducing agent under mild conditions [17,18]. In addition, stoichiometric oxidation of alkenes and C—H bonds by

---

Abbreviations: Por, porphyrin dianion; TMP, 5,10,15,20-tetramesitylporphyrin dianion; TPFPP, 5,10,15,20-tetrakispentafluorophenylporphyrin dianion; PhI(OAc)$_2$, iodobenzene diacetate; PhIO, iodosobenzene; TBHP, *tert*-butyl hydroperoxide; *m*-CPBA, *m*-chloroperoxybenzoic acid; 2,6-Cl$_2$PyNO, 2,6-dichloropyridine *N*-oxide.

* Corresponding author. Tel.: +1 270 745 3803; fax: +1 270 745 5361.
E-mail address: rui.zhang@wku.edu (R. Zhang).

http://dx.doi.org/10.1016/j.apcata.2014.04.014
0926-860X/© 2014 Elsevier B.V. All rights reserved.



Scheme 1. Catalytic oxidation of sulfides by ruthenium porphyrins (**1**) in the presence of $PhI(OAc)_2$ and visible light.

isolable $[Ru^{VI}(Por)O_2]$ revealed a useful insight into the mechanisms of the catalytic oxidation processes [9,14,19].

Although a large number of reports on the catalytic behavior of ruthenium porphyrins have appeared in the past two decades with major focus on alkene epoxidation and activated alkane hydroxylation, only very few studies have been reported with limited success on oxidation of sulfides by these well studied ruthenium porphyrins [20]. Recently, we have reported the kinetic studies of sulfide oxidation by the well characterized *trans*-dioxoruthenium(VI) porphyrins [21]. We have also shown that *trans*-dioxoruthenium(VI) porphyrin complexes can be readily produced by irradiation of porphyrin–ruthenium(IV) dichlorate complexes with visible light [22,23]. In this work, we aim to fully explore the potential of ruthenium porphyrins toward catalytic sulfoxidation reactions with iodobenzene diacetate, abbreviated as $[PhI(OAc)_2]$, which is commercially available and easy to handle. In contrast to the sacrificial oxidants in common use for metalloporhyrin catalyzed reactions, $PhI(OAc)_2$ does not show appreciable reactivity toward organic substrates or dose not damage the porphyrin catalysts under the usual catalytic conditions. Due to the mild oxidizing ability, $PhI(OAc)_2$ has been less often employed in the metalloporphyrin-catalyzed oxidations. Collman and Nam reported, respectively, the use of $PhI(OAc)_2$ as terminal oxidant for the iron(III) porphyrin catalyzed oxidation of hydrocarbons [24,25]. Adam and coworkers also described a highly selective oxidation of alcohols by chromium(III) salen with $PhI(OAc)_2$ [26]. In addition, Nishiyama and co-workers showed that $PhI(OAc)_2$ is a better oxidant than PhIO in ruthenium–pyridine-2,6-dicarboxylate complex-catalyzed epoxidation of *trans*-stilbene [27]. In the present study, we report that $PhI(OAc)_2$ is an efficient oxygen source associated with ruthenium porphyrins for the selective oxidation of sulfides to sulfoxides, which of catalytic efficiency is greatly enhanced by visible light irradiation (Scheme 1). In all cases, quantitative conversions of sulfides and exclusive selectivities for sulfoxides were obtained. Meanwhile, we show that a low-reactivity ruthenium(IV)–oxo porphyrin intermediate is detected by the oxidation of the ruthenium(II) carbonyl precursor with $PhI(OAc)_2$, which is ascribed to the observed excellent selectivity for sulfoxide. To the best of our knowledge, using $PhI(OAc)_2$ for the selective sulfoxidation reactions catalyzed by ruthenium porphyrin complexes is unprecedented.

2. Experimental

2.1. Materials and instrumentation

All commercial reagents were of the best available purity and were used as supplied unless otherwise specified. Iodobenzene diacetate or (diacetoxyiodo)benzene, $[PhI(OAc)_2]$, was purchase from Aldrich Chemical Co. and used as such. *m*-Chloroperoxybenzoic acid (*m*-CPBA) (77%) from Aldrich Chemical Co. was purified by precipitation–crystallization from methylene chloride and *n*-hexane, and then dried in vacuum. Iodosobenzene (PhIO) and *tert*-butyl hydroperoxide (TBHP) were purchased from the TCI America Co. and was used as obtained. All reactive substrates of organic sulfides for catalytic oxidations were passed through a dry column of active alumina (Grade I) before use. 5,10,15,20-Tetrakis(pentafluorophenyl)porphyrin (H_2TPFPP) was commercially available from Aldrich and used as received. 5,10,15,20-Tetramesitylporphyrin (H_2TMP) was prepared according to the known methods [28]. The corresponding ruthenium(II) carbonyl complexes $Ru^{II}(Por)(CO)$, $Ru^{IV}(Por)Cl_2$ and $Ru^{VI}(Por)O_2$ used for catalytic sulfoxidadtions were prepared by literature methods[14] and characterized by ^1H NMR, IR and UV–vis spectroscopies, matching those reported [14,17,29].

UV–vis spectra were recorded on an Agilent 8453 diode array spectrophotometer. IR spectra were obtained on a Bio-Rad FT-IR spectrometer. ^1H NMR was performed on a JEOL ECA-500 MHz spectrometer at 298 K with tetramethylsilane (TMS) as internal standard. Chemical shrifts (ppm) are reported relative to TMS. Gas chromatograph analyses were conducted on an Agilent GC6890/MS5973 equipped with a flame ionization detector (FID) using a DB-5 capillary column. The above GC/MS system is also coupled with an auto sample injector. Reactions of $Ru^{II}(Por)(CO)$ (**1**) with excess of $PhI(OAc)_2$ were conducted in a chloroform solution at $23 \pm 2\,°C$.

2.2. General procedure for photocatalytic sulfoxidations

In general, a Rayonet photoreactor (RPR-100) with a wavelength range of 400–500 nm ($\lambda_{max} = 420$ nm) from 300 W mercury lamps (RPR-4190 × 12) was used for the photocatalytic reactions. The photochemical reactions typically consisted of 0.5–1.0 mg of catalyst (approximate 0.5–1 μmol) in 2 mL of chloroform containing 0.5 mmol of organic substrates. 1.5 equivalent of $PhI(OAc)_2$ (0.75 mmol) was added to the reaction solution as it was irradiated at $25 \pm 2\,°C$. Aliquots of the reaction solution at constant time interval were analyzed by ^1H NMR or GC/MS to determine the formed products and yields with an internal standard (diphenylmethane). All reactions were run at least in duplicate, and the data reported represent the average of these reactions. Monitoring reaction by UV–vis spectroscopy before and after reactions indicated that no significant degradation of ruthenium catalyst was found after 24 h photolysis.

2.3. Catalytic competitive oxidations

A $CHCl_3$ solution containing equal amounts of two substrates, e.g. thioanisole (0.5 mmol) and substituted thioanisole (0.5 mmol), ruthenium(II) porphyrin catalyst (1 μmol) and an internal standard of diphenylmethane (0.1 mmol) was prepared (final volume = 2 mL). The internal standard was shown to be stable to the oxidation conditions in control reactions. $PhI(OAc)_2$ (0.4 mmol) as limiting reagent was added, and the mixture was irradiated under visible lights at ambient temperature ($25 \pm 2\,°C$) until the reaction was complete. Relative rate ratios for oxidations were determined based on the amounts of products (sulfoxides) by ^1H NMR or GC

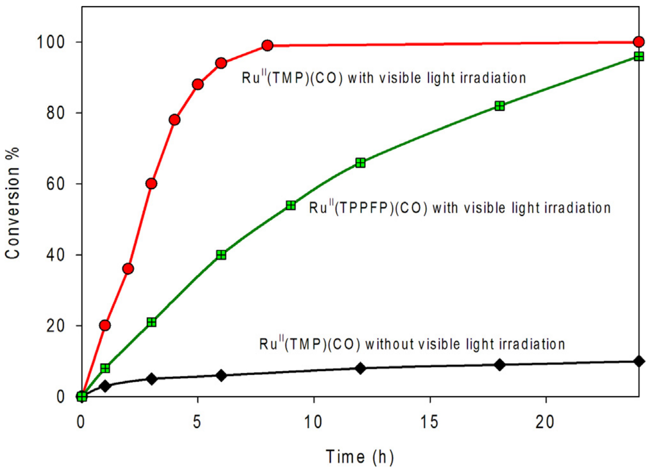


Fig. 1. Time courses of oxidation of thioanisole (0.5 mmol) with PhI(OAc)$_2$ (0.75 mmol) in CDCl$_3$ (2 mL) at room temperature catalyzed by **1** (1 μmol):, Ru^{II}(TMP)(CO) (**1a**) without visible light (diamond); Ru^{II}(TMP)(CO) (**1a**) with visible light (circle); Ru^{II}(TPFPP)(CO) (**1b**) with visible light (cube). Aliquots were taken at selected time intervals for product analyses with ^{1}H NMR.

(FID, DB-5). The values reported in Table 5 are the averages of 2–3 runs with a minor error (<5%).

3. Results and discussions

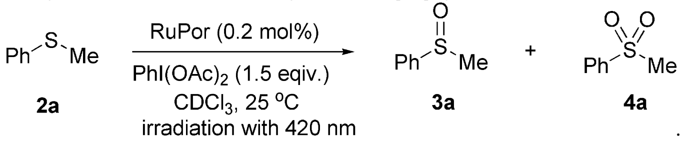
3.1. Screening the catalytic oxidation of thioanisole

Although the iodobenzene diacetate, PhI(OAc)$_2$, has been widely used as a mild oxidant for some time [25,27], apparently it had hitherto not been used for ruthenium porphyrin-catalyzed sulfoxidation reactions. Therefore, we have first investigated the PhI(OAc)$_2$ as oxygen source in the catalytic oxidation of thioanisole (**2a**) with different ruthenium porphyrin catalysts. Our immediate goal in this section was to identify the most efficient systems and optimal conditions from the screening reactions. In order to work under homogeneous conditions and follow the reaction course via ^{1}H NMR, the reactions were performed in CDCl$_3$ at room temperature using a 0.2 mol% catalyst loading and a 1:1.5 ration of thioanisole and PhI(OAc)$_2$. Our results collected in Fig. 1 and Table 1 show the carbonyl ruthenium(II) tetramesitylporphyrin (**1a**) catalyzed the oxidation of thioanisole very slowly, only ca. 10% conversion was observed after 24 h. Gratifyingly, under visible light irradiation (λ_{max} = 420 nm), the reaction proceeded much rapidly and thioanisole **2a** was smoothly and quantitatively oxidized to corresponding methyl phenyl sulfoxide (**3a**) in high yield and short reaction times (entry 2 in Table 1 and Fig. 1). The sulfoxide was the only identifiable oxidation product (>99% by GC) and the usual undesirable over oxidation of sulfoxide (**3a**) to sulfone (**4a**) was not observed, which manifests the high chemoselectivity of this reaction.

It has been well established that ruthenium(II) carbonyl porphyrins undergo photo-induced decarbonylation reactions [30]. The observed remarkable photo-stimulation with visible light was consistent with photoejection of the carbonyl ligand to generate the ruthenium(II) porphyrin that is much more active form of catalyst to react with PhI(OAc)$_2$. Therefore, all reactions were carried out under visible light irradiation in a Rayonet photoreactor. The control experiments show that no formation of sulfoxide (<5%) was detected when the reaction was carried out under light irradiation in the absence of either ruthenium porphyrin catalyst or PhI(OAc)$_2$. In addition, monitoring catalytic reaction by UV–vis spectroscopy indicated that the no significant degradation of porphyrin catalyst was observed under visible light photolysis (see Fig. S1 in the Supplementary material).

As expected, the catalytic activity (100% convn in 4 h) was enhanced with more PhI(OAc)$_2$ present (Table 1, entry 3). Instead of CDCl$_3$, the use of CD$_2$Cl$_2$ as the solvent resulted in a similar yield (entry 4). The reaction was also carried out in other solvents like toluene, diethyl ether, ethyl acetate, acetonitrile. Due to the poor solubility of PhI(OAc)$_2$ in all these solvents, much slower reactions were obtained with up to 30% conversions into products (data not shown). In terms of different oxidation states form of ruthenium catalyst, strikingly, the Ru^{IV}(TMP)Cl$_2$ proved to be completely inactive in the sulfoxidation reaction (entry 5), which is in marked contrast to the epoxidation of unfunctionalized alkenes with 2,6-dichoropyridine *N*-oxide, for which dichlororuthenium(IV) porphyrins are considerably more efficient compared to the carbonyl ruthenium(II) catalyst [16]. Much lower conversion was also observed in the oxidation of thioanisole catalyzed by Ru^{VI}(TMP)O$_2$ (entry 6). These results indicate that ruthenium(IV) and ruthenium(VI) are not accessible for the generation of active intermediate in the catalytic oxidation of sulfides by PhI(OAc)$_2$. The electron-deficient catalyst Ru^{II}(TPFPP)(CO) (**1b**),

Table 1
Catalytic oxidation of thioanisole by ruthenium porphyrins with iodobenzene diacetate under visible light irradiation[a]



Entry	Catalyst	*t* (h)	Convn (%)[b]	mb (%)[b]	Selectivity (**3a**:**4a**)[b]
1[c]	Ru^{II}(TMP)(CO)	24	10	>95	>99:1
2		6	94	>95	>99:1
3[d]		4	100	>95	>99:1
4[e]		6	92	>95	>99:1
5	Ru^{IV}(TMP)Cl$_2$	24	<5	>95	n.d.[f]
6	Ru^{VI}(TMP)O$_2$	24	15	>95	95:5
7	Ru^{II}(TPFPP)(CO)	24	90	>95	>99:1

[a] All reactions were conducted with visible light irradiation (λ_{max} = 420 nm) in a Rayonet reactor or otherwise noted. Reactions were carried out in CDCl$_3$ at ca. 25 °C with a 1:1.5 molar ratio of thioanisole versus PhI(OAc)$_2$ and 0.2 mol% catalyst at an initial substrate concentration of 0.25 M.

[b] Conversions (convn), mass balance (mb) and product selectivity were determined by ^{1}H NMR (JEOL 500 M) and/or quantitative GC–MS analysis on the crude reaction mixture after the reaction is quenched by sodium hydroxide solution (consuming all oxygen source).

[c] Without visible light irradiation.

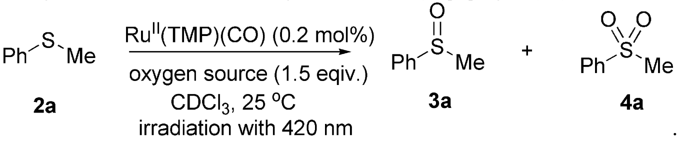
[d] 2 equivalent of PhI(OAc)$_2$ (1 mmol) was used.

[e] In CD$_2$Cl$_2$.

[f] n.d. = Not determined.

Table 2

Catalytic oxidation of thioanisole by the ruthenium(II) poprhyrin (**1a**) with various oxygen sources in the presence of visible light[a]



Entry	Oxygen source	t (h)	Convn (%)[b]	mb (%)[b]	Selectivity (**3a**:**4a**)[b]
1	PhI(OAc)$_2$	6	94	>95	>99:1
2	PhIO	12	89	96	91:9
3[c]	*m*-CPBA	12	100	92	45:55
4	TBHP	12	90	>95	93:7
5	2,6-Cl$_2$PyNO	24	33	>95	>99:1

[a] All reactions were conducted with visible light irradiation (λ_{max} = 420 nm) in a Rayonet reactor. Reactions were carried out in CDCl$_3$ at ca. 25 °C with a 1:1.5 molar ratio of thioanisole versus oxygen source and 0.2 mol% catalyst at an initial substrate concentration of 0.25 M.

[b] Conversions (convn), mass balance (mb) and product ratios were determined by ^{1}H NMR (JEOL 500 M) or by quantitative GC–MS analysis with an internal standard (diphenylmethane) on the crude reaction mixture after the reaction is quenched by sodium hydroxide solution (consuming all oxygen source).

[c] In the absence of the ruthenium(II) catalyst, control experiment shows *m*-CPBA gave 100% conversion with 70:21 ratio of sulfoxide versus sulfone over 24 h.

which has been used a robust catalyst in many oxidation reactions, also gave the sulfoxide exclusively. Compared to **1a**, **1b** was less reactive and a longer reaction time (24 h) was needed to observe a complete substrate conversion (entry 7).

3.2. *Comparison of various oxygen sources in the catalytic oxidation of thioanisole*

The promising results with the PhI(OAc)$_2$ in Table 1 prompted us to evaluate other common oxygen sources in the rutheniu(II) porphyrin-catalyzed oxidation of thioanisole for the intended purpose of comparison. A screening of diverse oxygen source under identical experimental conditions disclosed that the mild oxygen source PhI(OAc)$_2$ was especially effective for selective oxidation of sulfide to sulfoxide, as representative results are shown in Table 2. The use of more oxidizing oxygen source like iodosobenzene (PhIO), *m*-chloroperoxybenzoic acid (*m*-CPBA) or *tert*-butyl hydroperoxide (TBHP) gave quantitative conversions albeit with minor to significant sulfone formation (Table 2, entries 2–4). The most likely explanation is that these oxygen sources, having more oxidizing abilities, might generate more reactive oxidizing intermediates with ruthenium porphyrin catalyst than that with PhI(OAc)$_2$.[29,31] Similar to the catalytic expoxidation of unfunctionlized alkenes [13], 2,6-dichloropyridine *N*-oxide (2,6-Cl$_2$PyNO) as the oxygen source afforded excellent selectivity to sulfoxide, however, with a very poor conversion of 33% after 24 h (entry 5). Besides the high chemoselectivity, an additional advantage of the PhI(OAc)$_2$ compared to the other oxidants, is the fact that it will not cause the degradation of the porphyrin catalysts. Thus, a similar catalytic activity with excellent selectivity was achieved even at the very low catalyst loading of only 0.05 mol% (data not shown here).

3.3. *Catalytic oxidation of substituted thioanisoles and allylic sulfides by PhI(OAc)$_2$*

The substrate scope of the unprecedented catalytic sulfoxidations was explored under optimized conditions. Table 3 lists the oxidized products and corresponding selectivities using the **1a** and **1b** as the catalyst, respectively. In analogy with what we observed for **2a**, all catalytic oxidation of substituted thioanisoles proceeded with a quantitative conversion into the corresponding sulfoxides with excellent selectivity (100%) and mass balance (>95%), and in all cases no traces of sulfones were detected. Significant for preparative purposes, the reactions gave comparable yields in isolated products (entries 1 and 7).

We also followed the time courses of *para*-substituted thioanisoles oxidations by Ru^{II}(TMP)(CO) (**1a**) and PhI(OAc)$_2$ under visible light photolysis (Fig. 2). The introduction of electron-donating and electron-demanding substituents in the aryl ring of substrates gave a noticeable effect. As is evident, the introduction of electron-donating groups like methyl or methoxy groups resulted in increased reactivities compared to thioanisole (entries 5, 6, 11, 12 in Table 3), while reduced reactivities were observed in the presence of electron-demanding groups like Cl or Br groups. However, the log k_{rel} [$k_{rel} = k$(substituted thioanisole)/k(thioanisole)] versus Hammett substituent constant (σ_p) did not give a linear correlation for the catalytic oxidation of substituted sulfides under competitive conditions. Previously, we showed that the stoichiometric thioanisoles oxidation by *trans*-dioxoruthenium(VI) porphyrins in which cases both electron-donating and -withdrawing substituents moderately slow down the reactions [21]. Apparently, involvement of *trans*-dioxoruthenium(VI) species as the premier reactive intermediate in present study is implausible.

The present results demonstrate that the ruthenium porphyrin with PhI(OAc)$_2$ is an efficient catalytic system for the selective oxidation of sulfides. Its efficacy for epoxidation was also tested with *cis*-cyclooctene as substrates under the optimized reaction conditions. Surprisingly, no appreciable reactivity (<1% convn) was observed after 24 h for the unfunctionalized alkene. This result stimulates us to test this protocol for the oxidation of allylic sulfides.

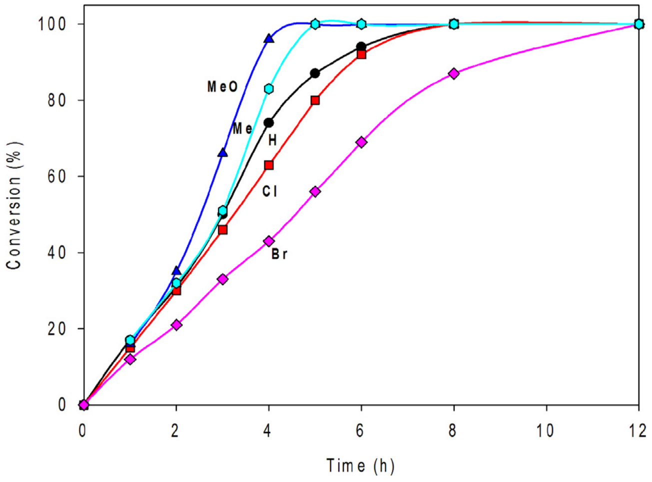
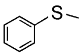
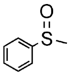
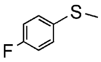
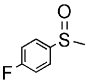
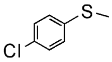
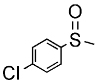
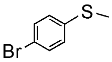
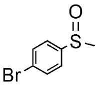
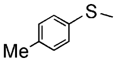
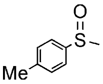
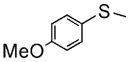
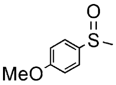
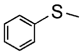
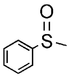
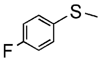
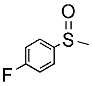
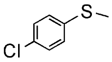
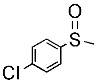
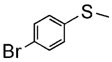
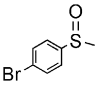
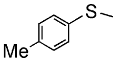
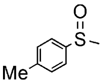
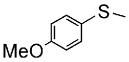
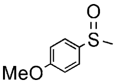


Fig. 2. Time courses of oxidation of *para*-substituted (4-X) thioanisoles (0.5 mmol) with PhI(OAc)$_2$ (0.75 mmol) in CDCl$_3$ (2 mL) at room temperature catalyzed by **1a** (1 μmol) under visible light irradiation. X = H (dot), MeO (triangle), Me (circle), Cl (square) and Br (diamond).

Table 3
Catalytic oxidation of substituted thioanisoles by ruthenium porphyrin (**1**) and $PhI(OAc)_2$ with visible light[a].

Entry	Catalyst **1**	Substrate **2**	Product **3**	Convn (%)[b]	Yield (%)[b]	Time (h)
1	Ru^{II}(TMP)(CO) **1a**			8	100	100 (90)[c]
2				6	100	100
3				8	100	100
4				12	100	100
5				5	100	100
6				4	100	100
7	Ru^{II}(TMP)(CO) **1b**			24	100	100 (93)[c]
8				6	100	100
9				8	100	100
10				6	100	100
11				6	100	100
12				6	100	100

[a] Unless otherwise specified, all reactions were carried out in $CDCl_3$ at ca. 25 °C in the presence of 1.5 equiv. of $PhI(OAc)_2$ and 0.2 mol% catalyst; only sulfoxide was detected by ^1H NMR or GC/MS analysis of the crude reaction mixture.

[b] Based on the conversion of thioanisoles and determined by ^1H NMR or GC/MS analysis of the crude reaction mixture; material balance > 95%.

[c] Isolated material after silica-gel chromatography with methylene and *n*-hexane as eluent.

The oxidation of sulfides in the presence of electron-rich double bonds is often problematic with many traditional oxidants such as *m*-CPBA, $NaIO_4$, and catalytic systems because of interference with epoxidations [3]. With ruthenium(II) catalyst and $PhI(OAc)_2$, no epoxidation took place and excellent chemoselectivities for sulfoxide were obtained albeit with somewhat low conversions (Table 4). Similarly, presence of hydoxy group did not disturb the selective oxidation of sulfide to sulfoixde and no alcohol oxidation was observed (entry 3 in Table 4).

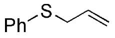
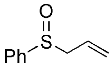
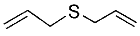
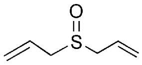
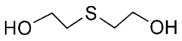
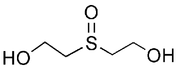
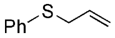
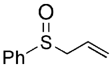
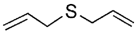
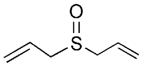
3.4. Mechanistic studies of active oxidizing species

Prior to the present studies, the use of ruthenium porphyrins for metal-catalyzed sulfoxidations has met with limited success in view of the low reactivity and, in most cases, undesirable over-oxidation to sulfones. We now show that ruthenium porphyrins catalyze the highly selective oxidation of thioanisoles and allylic sulfides by $PhI(OAc)_2$ in the presence of visible light. The preparative utility and synthetic value of the new catalytic system presented above are indisputable, but mechanistic understanding of the complex oxygen-transfer processes is important for the design of still more effective and selective oxidants with general applicability.

In fact, *trans*-dioxoruthenium(VI) porphyrin is capable of oxidizing olefins and activated hydrocarbons to undergo reduction [11]. However, the fact that no expoxidation or hydroxylation was observed in the catalytic oxidation of allylic/hydroxy sulfides by ruthenium porphyrin and $PhI(OAc)_2$ strongly suggests that *trans*-dioxoruthenium(VI) porphyrin is not a viable oxidizing intermediate in above catalytic cycle, even if it does have the ability to effect substrate oxidations.

To accentuate this point, the competitive sulfoxidation reactions catalyzed by carbonyl ruthenium(II) porphyrin complexes (**1**) with $PhI(OAc)_2$ were conducted as described in Section 2. The purpose of the competition studies is to evaluate whether the same species was active in the two sets of conditions by comparing the

Table 4
Catalytic oxidation of allylic or hydoxy sulfides by ruthenium porphyrin (**1**) and $PhI(OAc)_2$ with visible light[a].

Entry	Catalyst	Substrate	Product	Convn (%)[b]	Yield (%)b
1	RuII(TMP)(CO) **1a**			40	100
2					
3[c]				100	100
4	RuII(TPFPP)(CO) **1b**			32	100
5				64	100

[a] Unless otherwise specified, all reactions were carried out in $CDCl_3$ at ca. 25 °C in the presence of 1.0 equiv. of $PhI(OAc)_2$ and 0.2 mol% catalyst; only sulfoxide was detected by ^1H NMR analysis of the crude reaction mixture.

[b] Based on the conversion of thioanisoles and determined by ^1H NMR analysis of the crude reaction mixture; mass balance > 95%. The products were fully characterized by ^1H NMR after column chromatography.

[c] 1.5 equiv. of $PhI(OAc)_2$ was used.

ratios of products formed under catalytic turnover conditions to the ratios of rate constants measured in the direct kinetic studies [32]. If the same oxidant was present in both cases, the ratios of absolute rate constants from direct kinetic measurements and relative rate constants from the competition studies should be similar [33], although a coincident similarity for two different oxidants could not be excluded. When the ratios were not similar, however, the active oxidants under the two sets of conditions must be different [21,34].

Table 5 contains the results of kinetic results with *trans*-dioxoruthenium(VI) porphyrin complexes from our recent study [21] and competition reactions where $PhI(OAc)_2$ was employed as sacrificial oxygen source, respectively. Each sulfide substrate was oxidized to the corresponding sulfoxide in nearly quantitative yield based on the oxidant consumed. In this study, a limiting amount of $PhI(OAc)_2$ was used to keep the conversion less than 20% to avoid the effect of substrate concentration on the product ratios. As evident in Table 5, the results from the competition studies suggest that an unusually different behavior is apparent during catalytic turnover conditions with porphyrin–ruthenium(II) carbonyl complexes. For most of the cases, the ratios of absolute rate constants found in direct kinetic studies differed from the oxidation ratios for competition oxidation reactions of the two substrates. The differences appear to be statistically significant in the ratios of substrate oxidation rates. The oxidation rate ratios for each pair of substrates were found to be much more larger (more selective) when $PhI(OAc)_2$ employed compared to that from the absolute rate constants ratio of $Ru^{VI}(Por)O_2$, implying that the active oxidant generated under catalytic turnover condition with $PhI(OAc)_2$ should be less reactive than $Ru^{VI}(Por)O_2$. Therefore, a *trans*-dioxoruthenium(VI) is unlikely to be the active oxidant under turnover conditions.

To further probe the identity of the active oxidizing species under catalytic conditions, we conducted the chemical oxidation reaction of ruthenium(II) catalyst **1** by $PhI(OAc)_2$ in $CHCl_3$ in the absence of sulfides (Fig. 3). As shown in Fig. 3A, with five equivalent of $PhI(OAc)_2$, the precursor $Ru^{II}(TMP)(CO)$ (**1a**) was quantitatively converted to a species **5a** with clearly resolved isosbestic points. The absorption spectrum of **5a** with a weak Soret band at 406 nm and broad absorption bands around 550–750 nm was essentially identical to that of the known ruhenium(IV) mono–oxo porphyrin, which was independently prepared from a reported method[29] (the Supplementary material, Fig. S2). Further addition of $PhI(OAc)_2$ with up to 20 equivalent resulted in conversion of **1a** to another species **6a** with a red shift of the Soret band to 422 nm and blue shift of Q band to 518 nm, again with clean isosbestic points (Fig. 3B). The later signal of the final product is characteristic of the well-known *trans*-dioxoruthenium(VI) poprhyrin, i.e. $Ru^{VI}(TMP)O_2$ [31]. These

Table 5
Comparison of competition catalytic oxidations with ratios of absolute rate constants of *trans*-dioxoruthenium(VI) porphyrins[a].

Porphyrin system	Substrates	Method	k_{rel}[b]
TPFPP	*p*-Fluorothioanisole/thioanisole	Kinetic results	0.94
		$PhI(OAc)_2$	1.49
TPFPP	*p*-Chlorothioanisole/thioanisole	Kinetic results	0.71
		$PhI(OAc)_2$	3.22
TPFPP	*p*-Methylthioanisole/thioanisole	Kinetic results	0.66
		$PhI(OAc)_2$	2.23
TPFPP	*p*-Methoxythioanisole/thioanisole	Kinetic results	0.64
		$PhI(OAc)_2$	3.7
TMP	*p*-Fluorothioanisole/thioanisole	Kinetic results	0.375
		$PhI(OAc)_2$	1.47
TMP	*p*-Chlorothioanisole/thioanisole	Kinetic results	1.01
		$PhI(OAc)_2$	3.12

[a] A reaction solution containing equal amounts of two substrates, e.g., thioanisole (0.5 mmol) and substituted thioanisole (0.5 mmol), ruthenium(II) porphyrin catalyst (1 μmol) and an internal standard of diphenylmethane (0.1 mmol) was prepared in CH_3Cl (5 mL). $PhI(OAc)_2$ (0.4 mmol) was added, and the mixture was stirred overnight (12 h) under visible light irradiation at 25 °C.

[b] Relative ratios of absolute rate constants from kinetic results with *trans*-dioxoruthenium(VI) porphyrin complexes[21] and for competitive oxidations with carbonyl ruthenium(II) porphyrin catalysts (**1a** and **1b**). All competition ratios are averages of 2–3 determinations with standard deviations smaller than 10% of the reported values.

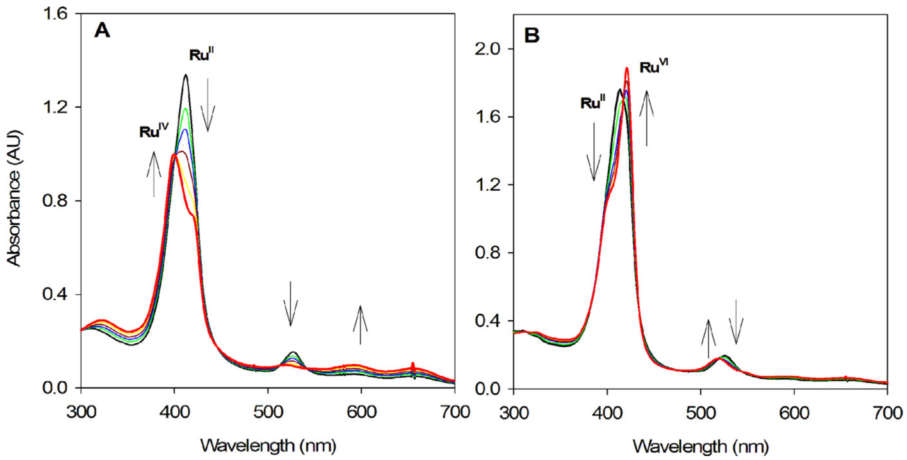
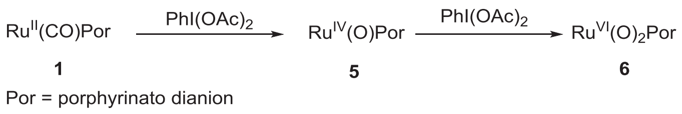


Fig. 3. Time-resolved spectrum for the oxidation of **1a** (5×10^{-6} M) with $PhI(OAc)_2$ in $CHCl_3$ (A) 5 equivalent of $PhI(OAc)_2$ over 40 min. (B) 20 equivalent of $PhI(OAc)_2$ over 20 min.

results unambiguously demonstrate that $PhI(OAc)_2$ can be used as a single oxygen atom source in generating *trans*-dioxoruthnium(VI) porphyrin via a monoruthenium(IV)–oxo intermediates (Eq. (1)). Of note, the formation of *trans*-dioxoruthenium(VI) porphyrin species (**6a**) was not observed for the same reaction but in the presence of organic sulfides.



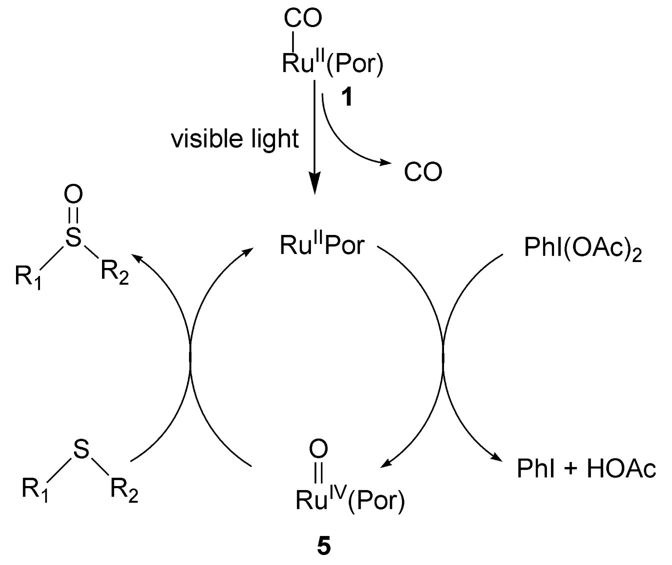
$$\underset{\mathbf{1}}{\mathrm{Ru^{II}(CO)Por}} \xrightarrow{\mathrm{PhI(OAc)_2}} \underset{\mathbf{5}}{\mathrm{Ru^{IV}(O)Por}} \xrightarrow{\mathrm{PhI(OAc)_2}} \underset{\mathbf{6}}{\mathrm{Ru^{VI}(O)_2Por}}$$

Por = porphyrinato dianion

(1)

It is well known that ruthenium(IV)–oxo porphyrins are much less reactive than the corresponding *trans*-dioxoruthenium(VI) porphyrins as the latter can oxidize the alkenes to expoxides and the former does not oxidize the alkenes but react with powerful reductants like triphenylposphine [35]. In this study, we found that ruthenium(IV)-oxo species (**5a**) when produced independently was competent oxidant and reacted rapidly with thioanisoles to generate the corresponding ruthenium(II) compound (Supplementary material, Fig. S3). Similarly, the electron-demanding $Ru^{VI}(TPFPP)O_2$ (**6b**) can be prepared by oxidation of the carbonyl precursor **1b** with 30 equivalent of $PhI(OAc)_2$, as shown by the close spectral agreement with the TMP analogue (Supplementary material, Fig. S4). Due to the electron-demanding nature, the oxidation of $Ru^{II}(TPFPP)(CO)$ to $Ru^{VI}(TPFPP)O_2$ is much slower than that of TMP analogue.

On the basis of the present experimental facts, a catalytic cycle is proposed in Scheme 2. First, visible light photolysis of carbonyl precursor **1** gives a more active ruthenium(II) species $Ru^{II}Por$**.** Second, oxidation of $Ru^{II}Por$ with $PhI(OAc)_2$ generated the ruthenium(IV)–oxo porphyrin (**5**) as the major oxidizing intermediate which subsequently oxidizes an organic sulfide selectively to sulfoxide without over oxidation to sulfone due to its low reactivity. After the oxygen transfer, the ruthenium(IV)-oxo species **5** then regenerates the precursor $Ru^{II}Por$ (Scheme 2). The pivotal formation of the low-reactivity ruthenium(IV)–oxo poprhyrin was unequivocally confirmed by the oxidation of **1a** with $PhI(OAc)_2$ in the absence of sulfide substrate (Fig. 3A). The notable absence of reactivity in the case of expoxidation and hydroxylation compared to sulfoxidation for the oxidation of allylic or hydroxy sulfides illustrates that the formation of more reactive *trans*-dioxoruthenium(VI) species is not directly involved in above catalytic cycle. We further assume that the formation of the ruthenium(IV)-oxo intermediate is the rate-determined step, which could explain the observed lower activity for the electron-demanding system **1b** in comparison to **1a**.



Scheme 2. A proposed catalytic cycle for the catalytic oxidations by the ruthenium(II) carbonyl porphyrin in the presence of $PhI(OAc)_2$ and visible light.

4. Conclusions

In conclusion, an efficient method for the highly selective oxidation of sulfides to sulfoxides with ruthenium porphrin as catalyst in the presence of $PhI(OAc)_2$ and visible light has been developed. All the factors that effected the catalytic sulfoxidation reactions were well investigated and understood. Various thioanisoles and allylic sulfides could be successfully oxidized with good conversions (most quantitative) and excellent selectivities. A plausible mechanism which relies on the generation of low-reactivity ruthenium(IV)-oxo intermediate has been proposed to account for the observed high selectivities. Further studies to define synthetic applications and characterize the observed transients more fully are underway in our laboratory.

Acknowledgments

This work was supported by the NSF grant (CHE-1213971) and an internal grant from WKU Office of Research (RCAP 12-8012).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apcata.2014.04.014.

References

[1] P. Kowalski, K. Mitka, K. Ossowska, Z. Kolarska, Tetrahedron 61 (2005) 1933–1953.

[2] S. Caron, R.W. Dugger, S.G. Ruggeri, J.A. Ragan, D.H.B. Ripin, Chem. Rev. 106 (2006) 2943–2989.

[3] J.E. Baeckvall, Modern Oxidation Methods, Wiley-VCH Verlag, Weinheim, 2004.

[4] E. Wojaczynska, J. Wojaczynski, Chem. Rev. 110 (2010) 4303–4356.

[5] R.A. Sheldon (Ed.), Metalloprophyrins In Catalytic Oxidations, Marcel Dekker, New York, NY, 1994.

[6] P.R. Ortiz de Montellano (Ed.), Cytochrome P450 Structure, Mechanism, and Biochemistry, third ed., Kluwer Academic/Plenum, New York, NY, 2005.

[7] B. Meunier (Ed.), Metal-Oxo and Metal-Peroxo Species in Catalytic Oxidations, Springer-Verlag, Berlin, 2000.

[8] B. Meunier, Chem. Rev. 92 (1992) 1411–1456.

[9] C.-M. Che, W.-Y. Yu, Pure Appl. Chem. 71 (1999) 281–288.

[10] J.T. Groves, K. Shalyaev, J. Lee, in: K.M. Kadish, K.M. Smith, R. Guilard (Eds.), The Porhyrin Handbook, Academic Press, 2000, pp. 17–40.

[11] C.-M. Che, J.-S. Huang, Chem. Commun. (2009) 3996–4015.

[12] X.-Q. Yu, J.-S. Huang, W.-Y. Yu, C.-M. Che, J. Am. Chem. Soc. 122 (2000) 5337–5342.

[13] H. Ohtake, T. Higuchi, M. Hirobe, Heterocycles 40 (1995) 867–903.

[14] 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. 11 (2005) 7040–7053.

[15] J.T. Groves, M. Bonchio, T. Carofiglio, K. Shalyaev, J. Am. Chem. Soc. 118 (1996) 8961–8962.

[16] R. Zhang, W.-Y. Yu, K.-Y. Wong, C.-M. Che, J. Org. Chem. 66 (2001) 8145–8153.

[17] J.T. Groves, R. Quinn, J. Am. Chem. Soc. 107 (1985) 5790–5792.

[18] T.-S. Lai, R. Zhang, K.-K. Cheung, C.-M. Che, H.-L. Kwong, Chem. Commun. (1998) 1583–1584.

[19] R. Zhang, W.-Y. Yu, H.-Z. Sun, W.-S. Liu, C.-M. Che, Chem. Eur. J. 8 (2002) 2495–2507.

[20] N. Rajapakse, B.R. James, D. Dolphin, Catal. Lett. 2 (1989) 219–226.

[21] C. Abebrese, Y. Huang, A. Pan, Z. Yuan, R. Zhang, J. Inorg. Biochem. 105 (2011) 1555–1561.

[22] Y. Huang, E. Vanover, R. Zhang, Chem. Commun. 46 (2010) 3776–3778.

[23] R. Zhang, Y. Huang, C. Abebrese, H. Thompson, E. Vanover, C. Webb, Inorg. Chim. Acta 372 (2011) 152–157.

[24] J.P. Collman, A.S. Chien, T.A. Eberspacher, J.I. Brauman, J. Am. Chem. Soc. 122 (2000) 11098–11100.

[25] J.H. In, S.E. Park, R. Song, W. Nam, Inorg. Chim. Acta 343 (2003) 373–376.

[26] W. Adam, S. Hajra, M. Herderich, C.R. Saha-Moller, Org. Lett. 2 (2000) 2773–2776.

[27] H. Nishiyama, Y. Motoyama, Chem. Commun. (1997) 1863–1864.

[28] J. Lindsey, R.D. Wagner, J. Org. Chem. 54 (1989) 828–836.

[29] W.-H. Leung, C.-M. Che, J. Am. Chem. Soc. 111 (1989) 8812–8818.

[30] M. Hoshino, Y. Kashiwagi, J. Phys. Chem. 94 (1990) 673–678.

[31] J.T. Groves, R. Quinn, Inorg. Chem. 23 (1984) 3844–3846.

[32] R. Zhang, M. Newcomb, Acc. Chem. Res. 41 (2008) 468–477.

[33] R. Zhang, J.H. Horner, M. Newcomb, J. Am. Chem. Soc. 127 (2005) 6573–6582.

[34] Z. Pan, R. Zhang, M. Newcomb, J. Inorg. Biochem. 100 (2006) 524–532.

[35] Y. Watanabe, H. Fujii, in: B. Meunier (Ed.), Metal-Oxo and Metal-Peroxo Species in Catalytic Oxidations, Springer-Verlag, Berlin, 2000.