Letter

# Novel reactivities of iodosylbenzene in the catalytic oxygenation of olefins

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## Abstract

Oxygenation of (carbonyl)osmium porphyrins provides *trans*-dioxoosmium(VI) porphyrins, which catalyze the reaction of olefins with iodosylarenes. The main reaction pathway is oxidative double bond cleavage, presumably through a hepta-coordinated osmium intermediate. Iodosylbenzene was also discovered to be an excellent initiator for the aerobic epoxidation of olefins in the presence of aldehydes under very mild reaction conditions. © 1999 Elsevier Science B.V. All rights reserved.

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A most outstanding discovery in the catalytic oxygenation of inactivated hydrocarbons is the ruthenium porphyrin catalyzed epoxidation of olefins, in which molecular oxygen is the primary oxygen atom source, without the requirement for any other additives [1,2]. Olefins are oxidized by the *trans*-dioxoruthenium(VI) porphyrin, resulting in epoxide and oxoruthenium(IV) porphyrin. The oxoruthenium(IV) intermediate disproportionates to *trans*-dioxoruthenium(VI) and ruthenium(II) and the latter complex reacts with molecular oxygen to form additional *trans*-dioxoruthenium(VI) porphyrin. The limitations of the ruthenium system are its almost exclusive restriction to the te-

tramesitylporphyrinato ligand, the reversible inhibition of the ruthenium(II) porphyrin intermediate by both the olefin and the produced epoxide and its irreversible inhibition by carbon monoxide formed by non-selective oxidation of the olefin (for a review about this reaction, see Ref. [3]). Regarding the related osmium complexes, the ligands-free osmium(II) porphyrins also react with $O_2$ to form *trans*-dioxoosmium(VI) porphyrins, but the literature reports about the reactivity of $[(POR)Os(O)_2]$ complexes toward organic substrates vary between zero and very low [4,5].

In the course of our studies with ruthenium and osmium porphyrins [6–8], we have now discovered that in contrast to the dioxygen-inert (carbonyl)ruthenium(II) porphyrins, the analogous osmium complexes do activate molecular oxygen (Eq. (1)). Thus, aerobic heating of

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[(TMP)Os(CO)] (20 mg in 50 ml toluene for 2 h at reflux) resulted in its quantitative transformation to [(TMP)Os(O)$_2$] (14 mg were isolated after recrystallization). [1] This extremely simple and clean procedure was also successfully applied for preparation of [(TTP)Os(O)$_2$] and [(OEP)Os(O)$_2$], which are not sterically protected against dimerization, an additional serious problem in ruthenium porphyrins.



$$(1)$$
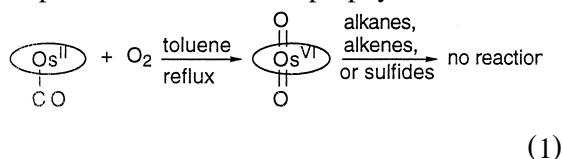
Encouraged by the clean formation of [(TMP)Os(O)$_2$], we have examined its reactivity for aerobic oxygenation of styrene, 4-methoxystyrene, norbornene, ethylbenzene and thioanisole, thus covering epoxidation, hydroxylation and sulfoxidations. Solvents used were benzene, toluene and ethylbenzene, both at room temperature and at reflux. In all cases, the very small amounts of oxygenated products were identical to that obtained in control reactions performed in the absence of the osmium complex. Accordingly, we may conclude that at least under these reaction conditions, [(TMP)Os(O)$_2$] is completely unreactive as oxygen atom transfer reagent. Following the reports of Hirobe and coworkers [9] about the unusually high reactivity of ruthenium porphyrin catalysts with pyridine-*N*-oxides as oxidants, we have also checked the combination of benzene solutions of styrene (175 mM), 2,6-dichloro-pyridine-*N*-oxide (162 mM) and osmium porphyrin (0.55 mM). The catalyst was added to the reaction mixture in various oxidation states—[(TMP)Os$^{II}$(CO)], [(TMP)Os$^{III}$(CO)(Br)], [(TMP)Os$^{III}$(CO)(ClO$_4$)] and [(TMP)Os$^{VI}$(O)$_2$] —but no more than traces of oxygenated organic products were obtained. Under these reaction conditions, [(TMP)Os$^{II}$(CO)] was quantitatively transferred to [(TMP)Os$^{VI}$(O)$_2$], but [(TMP)Os$^{III}$(CO)(Br)] and [(TMP)Os$^{III}$-(CO)(ClO$_4$)] remained unchanged. This is in contrast to the recent findings of Groves et al. [10] in the analogues ruthenium complexes, who have provided evidence for a ruthenium(III)–ruthenium(V) cycle in the Hirobe system.



$$(2)$$
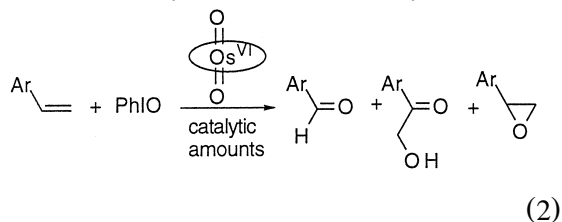
But, very different and quite novel results were obtained with iodosylbenzene as oxygen atom donor (Eq. (2)). A suspension of iodosylbenzene in a deaerated benzene solution of [(TMP)Os$^{VI}$(O)$_2$] and styrene became homogeneous in about 30 min. The major product was benzaldehyde, together with benzoyl hydroxide (an α-ketol) and some styrene oxide. Similar results were obtained for a variety of other aromatic olefins (Table 1). The chemical yields for this reaction, unprecedented in metalloporphyrin catalysis, were in the range of 60–100% —based on iodosylbenzene, the limiting reactant.

Examination of the relative reactivities of ring-substituted styrenes revealed that the electrophilicity of the oxygen-transfer-intermediate ($\rho = -2.0$) is much higher than that in the Lewis-acid catalyzed oxygenation of olefins by iodosylbenzene ($\rho = -1.1$) [11], but similar to the oxoiron(IV) porphyrin radical intermediate in iron porphyrin catalyzed epoxidations ($\rho = -1.9$) [12]. Still, the transition state geometries of these two reactions must be very different, since while in the present case both *trans*-stilbene and α-methylstyrene are more reactive than *cis*-stilbene (9:4:1, respectively and 10:6:1 with [(OEP)Os(O)$_2$] as catalysts), the iron and ruthenium porphyrin catalyzed epoxidation of *cis*-olefins are 14 to 40 times faster than those of the corresponding *trans*-olefins. Actually, the

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[1] Abbreviations used: TMP, OEP and TTP, the dianions of 5,10,15,20-tetra-(2,4,6-trimethylphenyl)porphyrin, 2,3,7,8,12, 13,17,18-octaethylporphyrin and 5,10,15,20-tetra-*p*-tolylporphyrin, respectively.

Table 1

Product distribution, chemical yields and relative reactivities in the $[(TMP)Os(O)_2]$ catalyzed reaction of olefins with iodosylbenzene (see Eq. (2))[a]

| | Ring-substituted-styrene | | | | | | | | trans-Stilbene | α-Methylstyrene | cis-Stilbene |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4-OCH₃ | 3-CH₃ | 4-F | H | 3-Cl | 4-Cl | 3-F | 3-NO₂ | | | |
| Aldehyde | 2.2 | 6.8 | 6.0 | 5.4 | 11.5 | 6.4 | 11.0 | 20.5 | 100 | 7.8[b] | 100 |
| α-Ketol | 1.1 | 2.9 | 4.5 | 4.0 | 4.8 | 3.0 | 5.0 | 1 | – | – | – |
| Epoxide | 1 | 1 | 1 | 1 | 1 | 1 | 1 | – | – | 1 | – |
| Total yield[c] | 60 | 74 | 66 | 71 | 67 | 66 | 66 | 47 | 100 | 100 | 86 |
| Relative reactivity[d] | 4.09 | 1.49 | 1.07 | 1.00 | 0.78 | 0.73 | 0.54 | 0.30 | 2.72[e] | 1.32[e] | 0.30[e] |

[a] Reaction conditions: 500 μmol olefin, 11 mg (50 μmol) iodosylbenzene and 0.25 mg (0.25 μmol) $[(TMP)Os(O)_2]$ in 0.5 ml benzene, at RT under Ar for 1 h.

[b] Ketone (acetophenone).

[c] Based on an inert standard, taking into account that formation of epoxide requires 1 equiv. of iodosylbenzene, while 2 equiv. are consumed for the production of α-ketol or aldehyde.

[d] Reaction conditions: as in (a), but with 1:1 mixtures of styrene and the other olefin.

[e] Competitions with 4-fluorostyrene and normalized relative to styrene.

higher reactivity of *trans*-olefins resembles that of osmium tetroxide catalyzed dihydroxylation [13]. Accordingly, we propose hepta-coordinated osmium porphyrins—which could be viewed as 'masked' osmium(VIII)—as feasible key intermediates in these reactions (Scheme 1).

The formation constant ($K_1$ in Scheme 1) of the first intermediate must be very small, as the $^1$H NMR spectrum of a benzene-$d_6$ solution of $[(TMP)Os(O)_2]$ was not affected by the addition

of iodosylbenzene and no iodobenzene was formed. Even after the addition of styrene, which initiated the formation of benzaldehyde and iodobenzene, the only osmium porphyrin observed in the spectrum was $[(TMP)Os(O)_2]$, i.e., all the intermediates proposed in Scheme 1 are short-lived and do not accumulate. Both proposed cyclic intermediates are reasonable, considering the stability of three-coordinated hypervalent iodine compounds such as iodobenzene
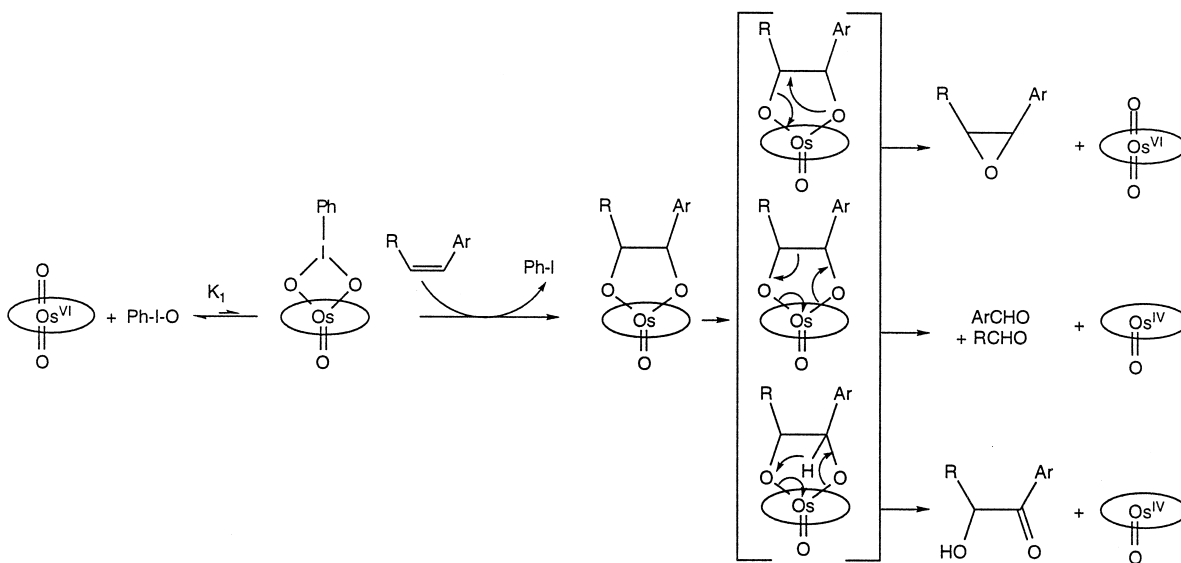


Scheme 1.

Table 2

Product distribution and turnover numbers (TON) in the $[(TMP)Os(O)_2]$ catalyzed oxidation of styrene with various oxidants[a]

| Oxidant | PhIO | $C_6F_5IO$ | MesIO[b] | $PhI(OAc)_2$ | PhIO | $Bu_4NIO_4$ | $NaClO_3$ [d] | NaOCl[e] |
|---|---|---|---|---|---|---|---|---|
| Solvent | Benzene | Benzene | Benzene | Benzene | $CH_3CN$[c] | Benzene | | |
| Aldehyde | 5.4 | 5.7 | 10.7 | 6.8 | 11.5 | 20 | 6.9 | 100 |
| $\alpha$-Ketol | 4.0 | 0.5 | 4.4 | 0 | 4.8 | 0 | 1 | 0 |
| Epoxide | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| TON[f] | 142 | 98 | 122 | 58 | 67 | 27 | 46 | 4 |
| Reaction time | 1 h | 1 h | 1 h | 1 h | 1 h | 5 days | 1 day | 2 h |

[a]Reaction conditions: 500 $\mu$mol olefin, 11 mg (50 $\mu$mol) oxidant and 0.25 mg (0.25 $\mu$mol) $[(TMP)Os(O)_2]$ in 0.5 ml solvent, at RT under Ar.
[b]1-Iodosyl-2,4,6-trimethylbenzene.
[c]$CH_3CN$/benzene: 2:1.
[d]37 mg $NaClO_3$ in 1 ml $H_2O$, 17 mg TBAP, 0.5 ml benzene.
[e]1 ml of 0.82 M $NaOCl/H_2O$, 17 mg TBAP, 0.5 ml benzene.
[f][(mol epoxide) + (2 × mol aldehyde) + (2 × mol $\alpha$-ketol)]/(mol catalyst), based on an inert standard.

diacetate $(PhI(OAc)_2)$ [14] and of osmium(VI) monoglycolate esters, respectively. We also show in Scheme 1 that one common intermediate can reasonably account for all the products. Examination of a variety of other solvents and oxidants for the oxygenation of styrene (Table 2) revealed that the major product in all cases was benzaldehyde and the remarkable efficiency of the iodosylarenes compared to the other oxidants. The superiority of iodosylarenes and the fact that even in the presence of water no diols were obtained support the proposed reaction mechanism—the cyclic intermediate and its *intramolecular* breakdown to products, respectively.

The above described reactions were also examined under aerobic conditions. To our surprise, the chemical yields relative to iodosylbenzene were found to exceed 100%. Examination of the possible factors which could possibly contribute to the aerobic oxidation led to the conclusion that the produced benzaldehyde is responsible. Thus, in the reaction of *cis*-stilbene with a 1:1 ratio of iodosylbenzene and 4-fluorobenzaldehyde the combined chemical yield of all products was 800% relative to iodosylbenzene and stilbene oxide and benzaldehyde were formed in an about equimolar ratio. Further investigations revealed that in the absence of $[(TMP)Os(O)_2]$ the reaction was much more

Table 3

Product distribution and chemical yields in the iodosylbenzene catalyzed aerobic oxygenation of olefins by the air/isobutyraldehyde system[a]

| Substrate | Products (ratio) | Yield (%) | Substrate | Products (ratio) | Yield (%) |
|---|---|---|---|---|---|
| Cyclooctene | cyclooctene oxide | 57 | *trans*-stilbene | *trans*-stilbene oxide (11) | 37 |
| | | | | benzaldehyde (1) | |
| Cyclohexene | cyclohexene oxide (27) | 47 | styrene | styrene oxide (7) | 23 |
| | 2-cyclohexene-1-ol (1) | | | benzaldehyde (2) | |
| | 2-cyclohexene-1-one (2) | | | phenylacetaldehyde (1) | |
| Norbornene | exo-2,3-epoxynorbornane (9) | 71 | *cis*-2-pentene[b] | *cis*-2-pentene oxide (2) | 41 |
| | endo-2,3-epoxynorbornane (1) | | | *trans*-2-pentene oxide (1) | |
| *cis*-Stilbene | *cis*-stilbene oxide (6) | 25 | vinylcyclohexane | cyclohexyl oxirane | 17.4 |
| | *trans*-stilbene oxide (25) | | | | |
| | benzaldehyde (1) | | | | |

[a]Reaction conditions: 72 mg (1 mmol) isobutyraldehyde, 0.5 mmol olefin and 8 mg (36 $\mu$mol) iodosylbenzene (added in two portions of 4 mg) in 1 ml benzene, at RT under air in the dark, for 4 h. The chemical yields are of the sum of products, relative to the olefin.
[b]Reaction performed in toluene and the *trans*-olefin produces only *trans*-epoxide in 47% chemical yield.

efficient, as well as more selective toward the production of epoxides. Also, non-aromatic aldehydes were more efficient as additives than benzaldehydes. Very good results were obtained with the combination of isobutyraldehyde and olefin in the ratio of 2:1 and catalytic amounts of iodosylbenzene (Table 3). The chemical yields relative to olefin were in the range of 17–71% for a range of olefins, with a large selectivity for production of epoxides. We must emphasize that although the $O_2$/aldehyde epoxidation system is long known and a subject of much research [15–17], the current reaction conditions are much milder. The reactions proceed with air (and not pure oxygen) [18], without light [19], or metal catalyst [20], or external heating. Some clue about the reactive species in the system is provided by the product distribution, especially the formation of *trans*-epoxides in the reactions of *cis*-stilbene and *cis*-2-pentene—*trans*/*cis* = 4.2 and 0.5, respectively and the significant amounts of endo-2,3-epoxynorbornane in the oxidation of norbornene. These results point toward a radical—probably isobutyric peroxy radical—rather than an ionic mechanism.



(3)

1.5:1, 64% yield



(4)

1:1.4, 86% yield
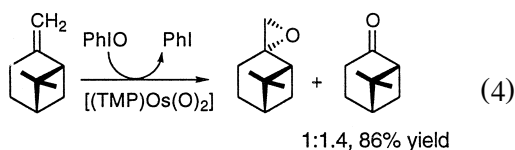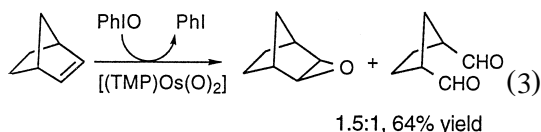
Finally, we present a few examples for the utilization of the reactions described in this study for synthetic purposes. The oxidative double bond cleavage of olefins is relevant for formation of dialdehydes from bicyclic olefins and of ketones from natural occurring olefins. Accordingly, we have used [(TMP)Os(O)$_2$] to catalyze the smooth reaction of iodosylbenzene

with norbornene and β-pinene, affording both the epoxides and the olefin-cleavage products in high total yields (Eqs. (3) and (4)). These reactions were successfully applied on a larger scale for preparation of *cis*-1,3-cyclopentane dicarboxaldehyde from norbornene and of nopinone from β-pinene (for ozonolysis of pinene and norbornene, see Refs. [21,22], respectively). [2] In both cases, the products were obtained under very mild reaction conditions and simple work up procedures, with less than 0.04 mol% of catalyst. Regarding the air/isobutyraldehyde/iodosylbenzene system, 0.8 g norbornene oxide were obtained from 1.88 g norbornene (36% isolated yield, based on olefin). [3]

In summary, we have discovered two new reaction modes of the commonly used iodosylbenzene—as a stoichiometric reagent for osmium porphyrin catalyzed oxidative bond cleavage of olefins and as a very effective initiator of the $O_2$/aldehyde epoxidation system.

## Acknowledgements

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[2] A total of 5.9 g (26.8 mmol) iodosylbenzene were added in portions during 7 days to a mixture of 2 ml (1*S*)-(−)-β-pinene (12.7 mmol), 2 ml benzene and 2 mg [(TMP)Os(O)$_2$] (2 μmol). Solvent evaporation and subsequent column chromatography (silica, *n*-hexane/EtOAc, 10/1) afforded 0.35 g (2.5 mmol, 20% yield) of pure (1*R*)-(+)-nopinone (GC and NMR compared to Aldrich product). Similarly, from 7 g iodosylbenzene, 1.5 g norbornene and 5 mg [(TMP)Os(O)$_2$] in 20 ml benzene, 0.29 g (14.5%) of pure *cis*-1,3-cyclopentane dicarboxaldehyde (GC and NMR compared to the product obtained by ozonolysis) [20] were obtained.

[3] A 100-ml light-protected flask was charged with 20 ml benzene, 1.88 g norbornene (19.6 mmol) and 2.82 g isobutyraldehyde (39.2 mmol). 160 mg (0.73 mmol) of iodosylbenzene were added to the stirred solution, followed by another 160 mg (0.73 mmol) of iodosylbenzene after 24 h. After another 24 h, the organic phase was washed with 2 M aqueous NaOH and the benzene was evaporated at room temperature and the product was purified by silica gel (*n*-hexane as eluent to remove iodosylbenzene, followed by *n*-hexane/ethylacetate 1:1 (v:v) to yield 0.8 g exo-norbornene oxide (7.14 mmol, 36.5%). The yield before the work up was 62%, as determined by GC.

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