

Oxidation of alkanes by iodosylbenzene (PhIO) catalysed by supported Mn(III) porphyrins: Activity and mechanism

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Received 9 December 2005; received in revised form 25 January 2006; accepted 26 January 2006

Available online 14 March 2006

Abstract

Manganese(III) tetrakis(2,6-dichloro-3-sulfonatophenyl)porphyrin (**1**) and manganese(III) tetrakis[tetrafluoro-4-(trimethylammonium)phenyl]porphyrin (**2**), in homogeneous solution and supported on modified silica surfaces, have been used as catalysts for the oxidation of pentane and cyclohexane with iodosylbenzene. The effects of reaction solvent, catalyst support and dioxygen on the oxidation yields and product distributions have been studied.

The reactions under nitrogen show a high selectivity for alcohol formation whereas in air ketones become significant products, indicating the participation of dioxygen in the formation of the ketones. Competitive oxidations of pentane and perdeuteropentane give kinetic isotope effects (k_H/k_D) of 6.9 ± 1.3 for both pentan-2-ol and -3-ol formation. The results are in accord with a mechanism in which an initial hydrogen atom-abstraction from the alkane by the active oxidant, an oxomanganese(V) species, gives a solvent-caged alkyl radical and a hydroxymanganese(IV) porphyrin. All the products can be accounted by partitioning of the carbon radicals between 'in cage' reaction to give alcohol and 'cage escape' leading to products typical of free alkyl radicals. The effect of solvent viscosity on this partitioning of the carbon radicals has been probed with the radical trap bromotrichloromethane.

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Keywords: Alkane oxidation; Manganese(III) porphyrin; Supported catalysts; Solvent viscosity; Kinetic isotope effect; Mechanism

1. Introduction

There is considerable interest in the oxidation of unactivated C–H bonds by biological systems since an understanding of the mechanisms of these reactions could lead to new industrial methods for the selective functionalisation of alkanes [1–5]. The most thoroughly studied of the oxidising enzymes are the cytochrome P450 monooxygenases which bring about a range of oxidations, including the hydroxylation of saturated C–H bonds [6–8]. Synthetic systems using iron and manganese porphyrins have been developed as chemical models for these enzymes and, based on studies of the enzymes and the models, mechanisms have been proposed for the functionalisation of C–H bonds involving high valent oxometal porphyrin species, such as $\text{Fe}^{\text{IV}}(\text{O})$ porphyrin π -cation radical and $\text{Mn}^{\text{V}}(\text{O})$ porphyrin, as the active oxidants [5,8–10].

Although all haem proteins contain iron in their active sites, research into the oxidation of alkanes with monooxygen donors, such as iodosylarenes, NaOCl and peroxides, catalysed by manganese porphyrin model systems has provided an important insight into the mechanisms of C–H oxidation and the factors that control the activity and stability of the catalyst [11–13]. In particular, it has shown that electron-withdrawing substituents on the *meso*- and/or β -pyrrole positions of the manganese porphyrins lead to improved catalysts for these reactions [14–16]. A further modification makes use of immobilisation of the catalyst on solid supports. This can, by the site-isolation of the manganese(III) porphyrins on/in a solid matrix, prevent their intermolecular self-oxidation and it can also make use of the support to modify the local environment of the catalyst [17–21]. Further advantages of supported catalysts are that they can aid separation of the products and allow the catalyst to be recovered and reused.

In this paper we describe our investigations into the influence of solvent and catalyst-support on the oxidation of pentane and cyclohexane by iodosylbenzene using two

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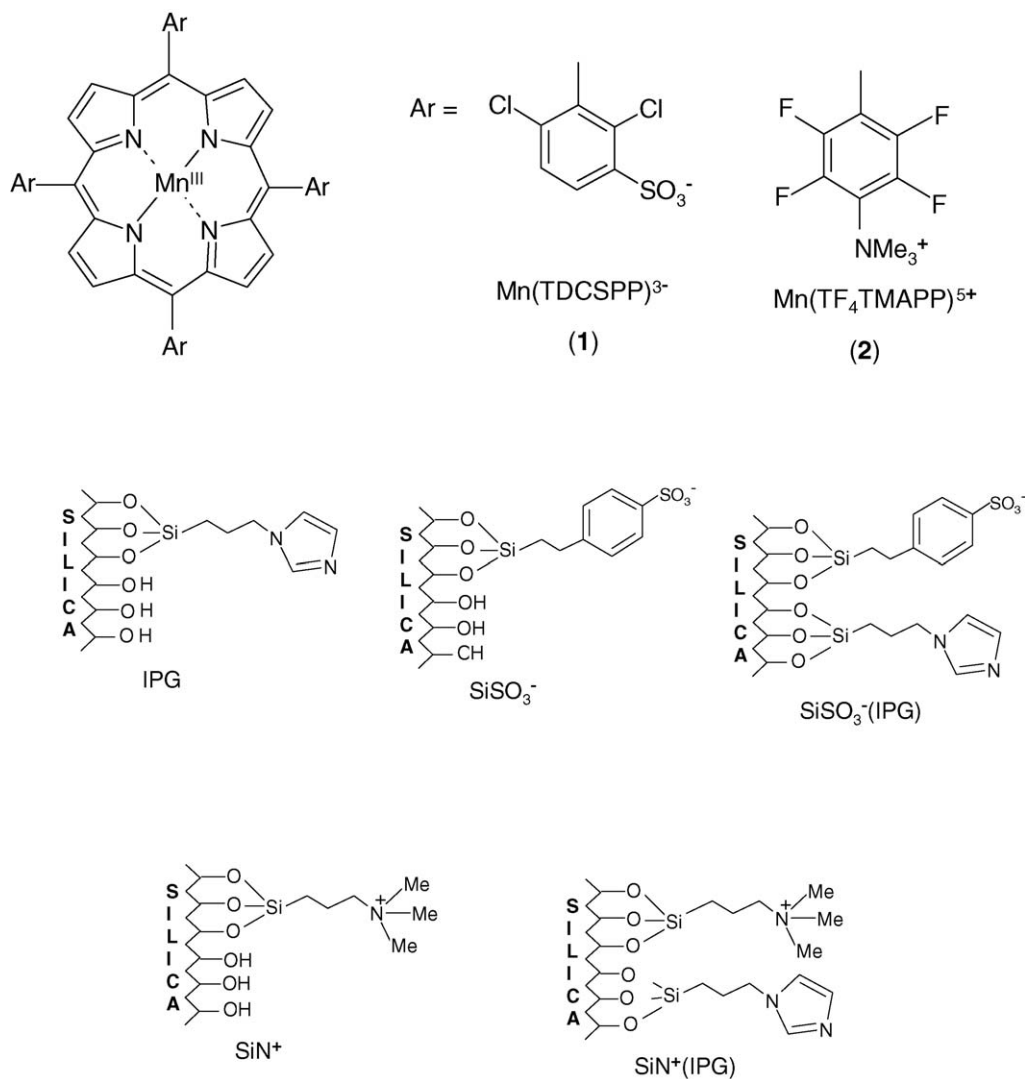


Fig. 1. Mn porphyrins and solid supports.

manganese(III) porphyrin catalysts, Mn(TDCSPP)³⁻ (1) and Mn(TF₄TMAPP)⁵⁺ (2) (Fig. 1). The majority of the oxidations have been carried out in air, however, selected reactions of cyclohexane have also been repeated in an inert atmosphere to obtain information about participation of dioxygen in these oxidations. Bromotrchloromethane has been used as a radical trap to probe the influence of the solvent on the reactions of the alkyl radical intermediates. Intermolecular kinetic isotope effects have been measured, by competitive oxidations of pentane and perdeuteropentane, and an overall mechanistic scheme to account for the results is presented.

2. Experimental

2.1. Instrumental methods

UV–vis spectra were recorded on a Hewlett-Packard 8453 diode array UV–vis spectrophotometer. Isothermal and temperature programmed GC was carried out on AMS94 and

Hewlett-Packard HP 6890 gas chromatographs with flame ionisation detectors using helium and nitrogen as carrier gases, respectively. Two capillary columns were employed; Supelco, MDN-5S (30 m × 0.25 mm i.d., film thickness 0.25 μm) and Hewlett-Packard, INNOWAX (30 m × 0.25 mm i.d., film thickness 0.25 μm). GC–MS studies used a VG Autospec S Series A027 mass spectrometer linked to a Hewlett-Packard 5890 Series 2 gas chromatograph.

2.2. Materials

All solvents and reagents were of commercial grade unless otherwise stated and were purchased from Fisher, Lancaster, Mallinckrodt, Carlo Erba or Aldrich. Pentane, dichloromethane, benzene, *N,N*-dimethylformamide, acetonitrile and acetone were HPLC or analytical reagent grade and were used as received. Perdeuteropentane (98 atom%) was obtained from Aldrich. Cyclohexane was purified by column chromatography on basic alumina prior to use and its purity was checked by gas chromatography. Iodosylbenzene, synthesised by the method of

Saltzmann and Sharefkin [22], was stored in a freezer and analysed every 6 months by iodometric assay.

2.3. Manganese(III) porphyrins and solid supports

The porphyrin ligand $\text{H}_2\text{TDCSPP}^{4-}$ and the Mn-complex $[\text{Mn}(\text{TF}_4\text{TMAPP})(\text{CF}_3\text{SO}_3)_5]$ (**2**) were purchased from Mid-century and used as received.

Manganese insertion into $\text{H}_2\text{TDCSPP}^{4-}$ was carried out by heating the free-base porphyrin with Mn^0 in dimethylformamide according to the method of Herrmann et al. [23] to give $\text{Mn}(\text{TDCSPP})(\text{Na})_3$, yield 98%; UV-vis: λ_{max} (CH_3OH) 374, 397, 468 ($1.2 \times 10^4 \text{ m}^2 \text{ mol}^{-1}$), 570 nm. ESI-MS: five most abundant peaks for $\text{Mn}(\text{TDCSPP})(\text{Na})^{2-}$, m/z 638.8, 639.9, 640.9, 641.9 and 642. 5 and for $\text{Mn}(\text{TDCSPP})^{3-}$, m/z 418.3, 419.1, 419.7, 420.3 and 421.0.

The catalyst supports, IPG, SiSO_3^- , $\text{SiSO}_3^-(\text{IPG})$, SiN^+ and $\text{SiN}^+(\text{IPG})$ (Fig. 1) were prepared and characterised as recently reported [19,24].

2.4. Preparation of supported catalysts

The supported catalysts were prepared by stirring a solution of **1** (in methanol) or **2** (in acetonitrile) with a suspension of the required support for 30 min at room temperature. All the supported catalysts were then filtered and exhaustively washed in a Soxhlet extractor (methanol for supported catalyst **1** and acetonitrile for supported catalyst **2**) for 15 h, dried at 100°C for 3 h and characterised by UV-vis spectroscopy as suspensions in tetrachloromethane. The loadings were quantified by measuring the amount of unloaded manganese(III) porphyrin, in the combined reaction solvent and washings, by UV-vis spectroscopy. The loadings obtained for all the supported catalysts were in the range 7.0–7.5 μmol of manganese(III) porphyrin per g of solid support.

2.5. Procedure for catalytic oxidations

Reactions were performed, at room temperature, in a 4 cm^3 vial, by adding iodobenzene ($1.2 \times 10^{-5} \text{ mol}$) to a stirred mixture of substrate ($2 \times 10^{-3} \text{ mol}$), catalyst ($1.2 \times 10^{-7} \text{ mol}$) and solvent (0.3 cm^3). For oxidations in an inert atmosphere, the reagents were thoroughly deoxygenated with argon or nitrogen prior to mixing in a vial capped with a Teflon-coated silicone septum. Yields, based on oxidant, were determined by removing aliquots from the reaction mixture and analysing them by GC, using bromobenzene as the internal standard. The products from selected reactions were also analysed by GC-MS. All reactions were run at least in duplicate.

2.6. Procedure for kinetic isotope effect (KIE) studies

The competitive oxidations between pentane and perdeuteropentane (molar ratio 1:1) were carried out as above and analysed by GC and GC-MS. The KIE values ($k_{\text{H}}/k_{\text{D}}$) for formation of pentan-2-ol and pentan-3-ol were obtained by comparison of GC-MS spectra of alcohol products

and also by comparing the GC peak areas of the deuterated and undeuterated alcohols.

3. Results and discussion

3.1. Oxidation of pentane and cyclohexane in air

Two manganese porphyrins, $[\text{MnTDCSPP}]^{3-}$ (**1**) and $[\text{Mn}(\text{TF}_4\text{TMAPP})]^{5+}$ (**2**), in homogeneous solution and supported on silica gel and five different, chemically modified silica gels (Fig. 1), were used in this study. Typical reaction conditions involved stirring a suspension of iodobenzene with the Mn^{III} porphyrin catalyst and pentane or cyclohexane in the solvent (acetone, benzene, 1,2-dichloroethane or dichloromethane), in the molar ratio of catalyst:oxidant:substrate of 1:100:17,000. Under aerobic conditions all the Mn^{III} porphyrin systems catalysed the oxidation of pentane and cyclohexane by iodobenzene. No reaction products were detected in control reactions in the absence of the Mn^{III} porphyrin catalysts.

The % yields of the products, based on the oxidant, and the alcohol:ketone ratio for each reaction are recorded in Tables 1 and 2. The overall product yields from the less reactive substrate, pentane, show a greater dependence on catalyst (4–40%) than those from cyclohexane (37–55%). In general, **2** was a more efficient catalyst for pentane oxidation than **1**, whereas for cyclohexane both catalysts had comparable activity. However, no consistent trends of yields with catalyst support are evident. Thus for example, the presence of imidazole groups on the support surface, which might be expected to ligate to the metal centre, appears to improve the oxidation of pentane catalysed by **1** but this is not seen in the oxidation of cyclohexane nor with the oxidations using catalyst **2**. Changing the solvent from dichloromethane to benzene or acetone did not have a marked effect on the overall yields although oxidations in benzene, in the main, had the highest conversions.

Complete gas chromatographic separation of the three alcohols and two ketones from the oxidation of pentane has not normally been accomplished in previous studies [25,26]. However, it was achieved in this investigation, allowing a comprehensive analysis of the pentane oxidation products. This shows that effectively all the products arise from oxidation of the secondary C–H bonds; only trace quantities of primary C–H oxidation products from pentane were detected. The latter were not quantified. This strong preference for reaction at the secondary C–H bonds contrasts with the minimal discrimination between the two secondary positions. Thus for all the oxidations with catalyst **2**, in homogeneous solution and on each of the four supports [SiO_2 , IPG, SiSO_3^- and $\text{SiSO}_3^-(\text{IPG})$], the ratio of pentan-2-ol to -3-ol and of pentan-2-one to -3-one are close to the statistical value of 2:1. With catalyst **1** the ratios are slightly larger (3 or 4:1) showing that, for the latter more hindered manganese(III) porphyrin, there is a small selectivity for the less hindered 2-position of pentane.

The results above show that the influence of the supports on the regio-selectivity of the oxidations is very small, thus it appears that anchoring the porphyrin to the support by electrostatic (coordinative) interactions has little effect on the catalyst's

Table 1
Product yields^a from the oxidation of pentane with PhIO catalysed by Mn^{III} porphyrins in air (under nitrogen)

Entry	Catalyst (solvent ^b)	C ₂ -ol (%)	C ₃ -ol (%)	C ₂ -one (%)	C ₃ -one (%)	A/K ratio	Total yield (%)
1	1 Homogeneous (i)	2	<0.5	2.5	1	0.7	6
2	1 -SiN ⁺ (i)	3	0.5	2	1	1.2	6.5
3	1 -SiN ⁺ (ii)	2	0.5	1	<0.5	1.7	4
4	1 -SiN ⁺ (iii)	13	3	7	2	1.8	25
5	1 -SiN ⁺ (IPG) (i)	9	3	4	1.5	2.2	18
6	1 -SiN ⁺ (IPG) (ii)	4.5	1.5	1	<0.5	4.0	7.5
7	1 -SiN ⁺ (IPG) (iii)	15	4	2.5	<0.5	6.3	22
8	2 Homogeneous (i)	15 (23)	6 (9)	5 (1)	2 (0.5)	1.6 (21)	28 (33)
9	2 -SiO ₂ (i)	5	2	3	2	1.4	12
10	2 -SiO ₂ (ii)	6	3	2.5	1	2.6	13
11	2 -SiO ₂ (iii)	6	3.5	4	2	1.6	16
12	2 -IPG (i)	7 (27)	3 (10)	5 (2)	2 (0.5)	1.4 (14.8)	17 (40)
13	2 -IPG (ii)	8	4	1.5	1	4.8	15
14	2 -IPG (iii)	17	7.5	3.5	1.5	4.9	30
15	2 -SiSO ₃ ⁻ (i)	12 (26)	4.5 (10)	5 (2)	2 (0.5)	2.4 (14.4)	23 (39)
16	2 -SiSO ₃ ⁻ (ii)	17 (17)	8 (7)	3 (1)	1.5 (0.5)	5.6 (16)	29.5 (26)
17	2 -SiSO ₃ ⁻ (iii)	16 (10)	8 (5)	5.5 (1.5)	2.5 (0.5)	3 (7.5)	32 (17)
18	2 -SiSO ₃ ⁻ (IPG) (i)	9.5	4.5	5	2.5	1.9	22
19	2 -SiSO ₃ ⁻ (IPG) (ii)	19	8	3	1.5	6	32
20	2 -SiSO ₃ ⁻ (IPG) (iii)	20	9.5	4	1.5	5.4	35

^a Yields based on PhIO after 24 h reaction, since the PhIO:catalyst ratio is 100, these values are also the catalyst turnover numbers. The values in parentheses are from reactions under an inert atmosphere. The yields for pentan-1-ol are <0.5%.

^b (i) Acetone, (ii) dichloromethane and (iii) benzene.

reactivity or on the access of the substrate to the active oxidant. Likewise, comparison of the product distributions from reactions in different solvents reveals that the regio-selectivity of the oxidation has no obvious dependence on the solvent.

Since catalyst **2** gave better yields from pentane oxidations it was selected in preference to catalyst **1** for more detailed mechanistic studies (see below).

3.2. Oxidation of pentane and cyclohexane under nitrogen

To investigate the role of dioxygen in these reactions, some of the oxidations, catalysed by **2**, were also carried out under nitrogen. In all the reactions this led to a reduction in ketone formation, showing that dioxygen is intimately involved in the formation of the ketones. This is considered in more detail in the mechanistic discussion below. A consequence of the reduced

yield of ketone is a marked increase in selectivity for alcohol over ketone. This is particularly obvious for the reactions in acetone, where the alcohol yields increase in an inert atmosphere (Table 1, entries 12 and 15).

The supported catalyst **2**-SiSO₃⁻, in particular, shows promise in the oxidation of alkanes to alcohols under mild conditions. For pentane oxidation, especially under nitrogen, moderate yields were accompanied by high selectivity for alcohols.

3.3. The mechanism of alkane oxidation

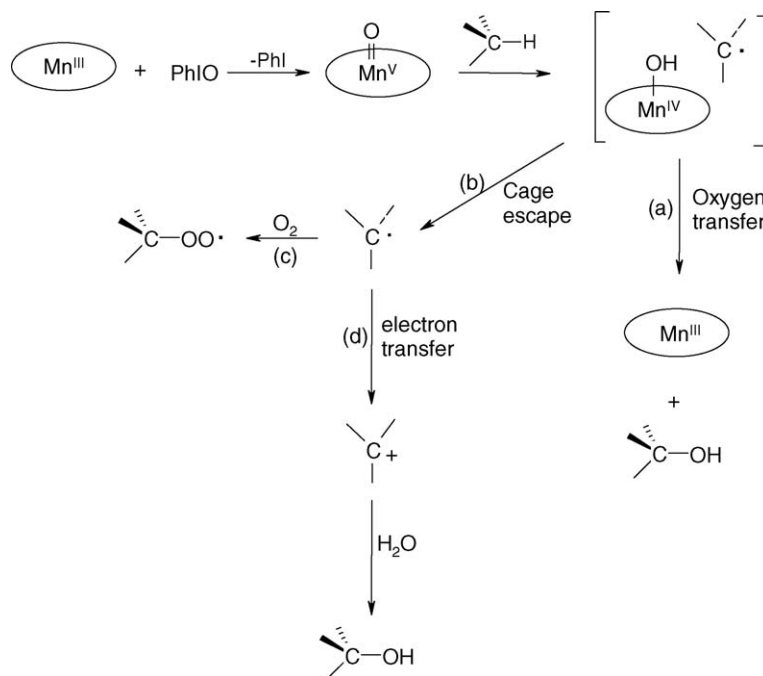
Previous studies by the groups of Groves [11], Hill [27,28] and others [29,30] have led to the conclusion that oxygen transfer, in the manganese(III) porphyrin-catalysed hydroxylation of unactivated C–H bonds by iodosylbenzene, involves two

Table 2
Product yields^a from the oxidation of cyclohexane with PhIO catalysed by Mn^{III} porphyrins in air (under nitrogen)

Entry	Catalyst (solvent ^b)	Cyclohexanol (%)	Cyclohexanone (%)	A/K ratio	Total yield (%)
1	1 -SiN ⁺ (i)	22	15	1.5	37
2	1 -SiN ⁺ (iii)	34	16	2.1	50
3	1 -SiN ⁺ (IPG) (i)	28	13	2.2	41
4	1 -SiN ⁺ (IPG) (iii)	38	14	2.7	52
5	2 homogeneous (i)	40 (38)	15	2.7	55 (38)
6	2 -IPG (i)	26	16	1.6	42
7	2 -IPG (iii)	33	13	2.5	46
8	2 -SiSO ₃ ⁻ (i)	26 (32)	16 (11)	1.6 (2.9)	42 (43)
9	2 -SiSO ₃ ⁻ (ii)	34	13	2.6	47
10	2 -SiSO ₃ ⁻ (iii)	36 (27)	16	2.2	52 (27)
11	2 -SiSO ₃ ⁻ (IPG) (i)	32	15	2.1	47

^a Yields based on PhIO after 24 h reaction, since the PhIO:catalyst ratio is 100, these values are also the catalyst turnover numbers. The values in parentheses are from reactions under an inert atmosphere.

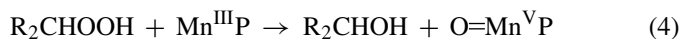
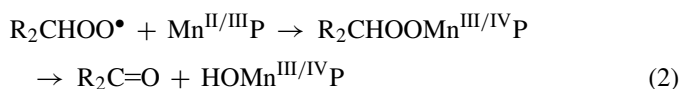
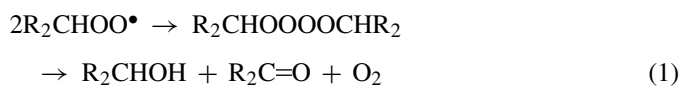
^b (i) Acetone, (ii) dichloromethane and (iii) benzene.



Scheme 1. The mechanism of the Mn(III) porphyrin-catalysed oxidation of alkanes by PhIO, showing alternative competing pathways following formation of initial solvent-caged alkyl radical and hydroxymanganese(IV) porphyrin.

steps. In the first, hydrogen atom abstraction by an oxomanganese(V) porphyrin generates a solvent-caged alkyl radical and a hydroxymanganese(IV) species. Subsequent ‘in cage’ reaction gives the alcohol (Scheme 1, pathway a). However, in competition with the second step, the carbon radicals can escape from the solvent cage (Scheme 1, pathway b) and react to give a number of other products. It is noteworthy that in manganese(III) porphyrin-catalysed oxidations, there is more cage escape of the alkyl radical than with the equivalent iron(III) porphyrin-catalysed reactions due to the relative stability of the intermediate $[\text{Mn}^{\text{IV}}(\text{OH})\text{por}]^+$ compared to the corresponding iron-complex [31].

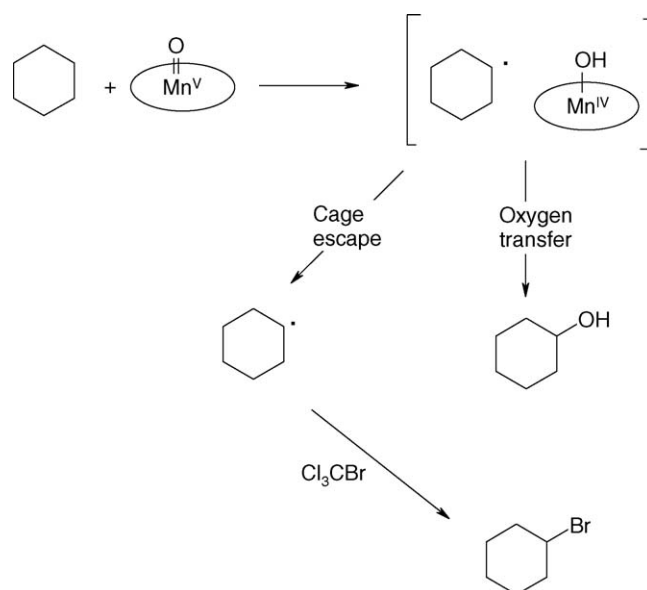
In aerobic solution, the predominant ‘out of cage’ reaction is trapping by dioxygen (Scheme 1, pathway c; rate constant $>10^9 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$ [32]) to give alkylperoxy radicals. Subsequent reactions of the latter radicals include dimerisation and cleavage of the tetroxide to an alcohol and a ketone (Reaction (1), Russell mechanism [33]) and complexation with manganese porphyrin followed by elimination to give a ketone (Reaction (2)). The latter pathway has been suggested previously for the reaction of peroxy radicals with iron(III) and iron(II) porphyrins [34,35]. H-atom abstraction (Reaction (3)) is energetically unfavourable and unlikely to play a significant role in these reactions [36]. However, any hydroperoxides formed in Reaction (3) will be reduced to alcohol by manganese(III) porphyrin (Reaction (4)) [37,38].



The fate of the alkyl radicals that escape the solvent cage in the reactions under nitrogen is less clear. However, in the absence of the radical scavenger dioxygen, they would be expected to give non-oxygenated products, by dimerisation (for example dicyclohexyl from cyclohexane [27]), disproportionation and hydrogen atom-abstraction, leading to a decrease in the total yield of alcohols and ketones. A reduction in yield is observed for the reactions in benzene and dichloromethane but interestingly not in acetone. With this solvent the alcohol and total alcohol/ketone yields are higher under nitrogen than in air. Since acetone is the most polar of the solvents used, we propose that in this solvent some of the alkyl radicals that would have been trapped by dioxygen in aerobic conditions undergo single electron-transfer oxidation, by manganese(III) and (IV) species. Smegal and Hill [28] showed that this pathway does not occur in the hydroxylation of primary C–H bonds but that it is a likely pathway for tertiary C–H bonds by iodobenzene and manganese(III) tetraphenylporphyrin even in the non-polar solvent, dichloromethane. In the present study, we believe that the combination of electron-withdrawing substituents on the porphyrins and the polar solvent would be sufficient, in the absence of dioxygen, to favour single electron transfer oxidation of the secondary radicals to carbocations. These would react further to give alcohols (Scheme 1, pathway d). This pathway has also been suggested for oxidations catalysed by iron(III) porphyrins. Thus Auclair et al. [39] proposed it in the oxidation of norcarane by cytochrome P450 monooxygenases and Bruice and coworkers invoked the reduction of iron(III) porphyrins by methyl radicals to account for the formation of

iron(II) tetrakis(2,6-dimethyl-3-sulfonatophenyl)porphyrin in the anaerobic reaction of the iron(III) complex with *t*-butyl hydroperoxide [40]. Brault and Neta [41] have shown that the oxidation of methyl radicals by iron(III) deuteroporphyrin, in water (pH 7), occurs very rapidly ($1.3 \times 10^9 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$). In support of this mechanism, UV–vis spectroscopy shows the formation of a manganese(II) porphyrin species (λ_{max} 452 nm) in the anaerobic, $\text{Mn}(\text{TF}_4\text{TMAPP})^{5+}$ -catalysed oxidation of pentane by iodosylbenzene in acetone (Supplementary Fig. S1).

To investigate the importance of carbon-centred radicals in these alkane oxidations, the reaction of cyclohexane using 2-SiSO_3^- was carried out under air, in the presence of the radical trap bromotrichloromethane (molar ratio, catalyst:PhIO:BrCCl₃:cyclohexane, 1:100:150:17,000) in four solvents (acetone, benzene, 1,2-dichloroethane and dichloromethane). A significant amount of bromocyclohexane was formed in each reaction. The total product yields (alcohol, ketone and bromoalkane) remained essentially the same as those in the absence of the radical trap, indicating that the radical trap and dioxygen effectively consume all carbon radicals that escape the solvent cage and the oxygenated products formed outside the solvent cage do not arise from an autoxidative chain reaction (cf. entries 8–10 in Table 2 with values from comparable reactions in Table 3). Interestingly the relative proportion of cyclohexanol, formed predominantly by ‘in cage’ oxygen-rebound, to bromocyclohexane, from an ‘out of cage’ reaction (Scheme 2) shows a marked dependence on solvent; 1,2-dichloroethane gives the highest alcohol to bromoalkane ratio (5.6) and acetone the lowest (1.1). We suggest that this arises from the solvent’s viscosity controlling the lifetime of the solvent cage and hence the relative proportions of ‘in cage’ to ‘out of cage’ reactions of the cyclohexyl radical. Thus with 1,2-dichloroethane, the most viscous solvent studied, the ‘in cage’ reactions dominate, whereas with acetone the least viscous solvent ‘in cage’ and ‘out of cage’ reactions are about equivalent. The results from the remaining solvents fit as expected between the two extremes. A similar effect was observed by Tanner and Rahimi, studying the reactions of *t*-butyl radicals from the photolysis of azoisobutane in the presence of the radical trap thiophenol, where increasing the solvent’s viscosity was shown to favour ‘in cage’ self-reaction over ‘out of cage’ trapping [42]. Comparable solvent viscosity effects on the reactions of caged radical pairs have also been reported for *t*-butoxyl [43] and cumylperoxyl radicals [44]. Katsuki and coworkers used increased solvent viscosity to enhance the enantioselectivity of benzylic hydroxylation with iodosylbenzene catalysed by chiral manganese(III) salens [45] by favouring ‘in



Scheme 2. Trapping of cyclohexyl radical in the hydroxylation of cyclohexane with iodosylbenzene catalysed by a manganese(III) porphyrin.

cage’ reaction of the benzyl radical intermediates (cf. Scheme 1, pathway a).

Comparison of the product distributions from reactions in air with those under nitrogen reveals that, with all the catalysts derived from manganese(III) porphyrin **2**, the large majority of the ketone products arise from ‘out of cage’ trapping of the carbon radicals by dioxygen. A minor pathway involving further oxidation of the alcohols would account for the traces of ketones formed under nitrogen. Thus in an inert atmosphere, the reactions are very selective for alcohol formation with little over-oxidation to ketone. A similar observation was made recently by Feringa and coworkers who noted a dramatic increase in the alcohol to ketone ratio in the iron(II) *N,N*-bis(2-pyridylmethyl)-*N*-bis(2-pyridyl)methylamine-catalysed oxidation of alkanes by peroxyacids when carried out in the absence of air [47].

Further information about the mechanisms of these catalysed oxidations was obtained by measuring intermolecular kinetic isotope effects ($k_{\text{H}}/k_{\text{D}}$) from competitive oxidations of pentane and perdeuterated pentane using catalyst **2**. These reactions were carried out under the standard conditions, where the conversion of the substrates was low (<0.5%). This ensured that the relative concentrations of the substrates effectively remained constant during the course of the oxidation. The $k_{\text{H}}/k_{\text{D}}$ values were determined by GC–MS and also by GC analysis since the deuterio-alcohols were readily separated from their protio-

Table 3

Yields of products^a from the oxidation of cyclohexane with PhIO catalysed by 2-SiSO_3^- in the presence of bromotrichloromethane

Solvent (viscosity/mPa ^b)	C ₆ H ₁₁ OH (%)	C ₆ H ₁₀ O (%)	C ₆ H ₁₁ Br (%)	Total yield (%)	C ₆ H ₁₁ OH/C ₆ H ₁₁ Br ratio
1,2-Dichloroethane (0.779)	39	n.d.	7	46	5.6
Benzene (0.604)	36	3	7	46	5.1
Dichloromethane (0.413)	30	2	10	42	3.0
Acetone (0.306)	19	3	18	40	1.1

^a Yields based on PhIO after 24 h, since the PhIO:catalyst ratio is 100, these values are also the catalyst turnover numbers.

^b Viscosity at 25 °C [46].

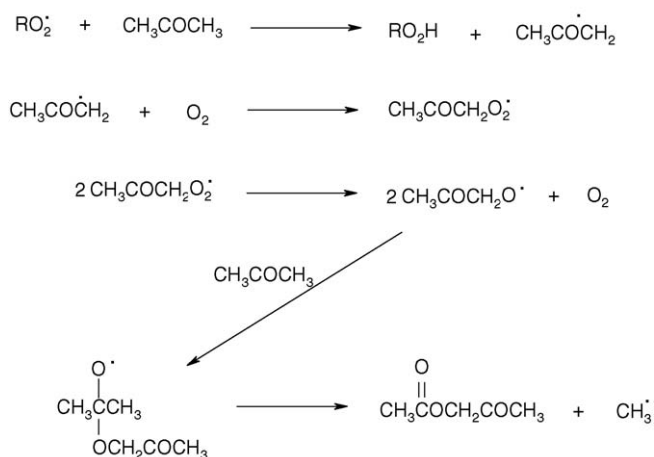
Table 4
Intermolecular kinetic isotope effects determined from competitive oxidations of pentane and perdeuteropentane with iodosylbenzene and catalyst **2**

Catalyst	Solvent/conditions	k_H/k_D for 2-ol by GC–MS and (GC-FID)	k_H/k_D for 3-ol by GC–MS and (GC-FID)
2 -SiSO ₃ [−]	Acetone/air	5.7 (7.5)	6.0 (7.7)
2 -SiSO ₃ [−]	Benzene/air	6.1 (n.d. ^a)	6.1 (n.d. ^a)
2 Homogeneous	Acetone/air	6.9 (7.8)	7.0 (8.2)
2 Homogeneous	Acetone/nitrogen	5.8 (6.5)	5.6 (6.4)

^a Not determined, impurities in the solvent interfered with GC-FID analysis.

analogues. Both sets of data are in good agreement (Table 4) and show that the intermolecular isotope effects for pentan-2-ol and -3-ol formation, using both the homogeneous and heterogeneous systems lie in the range $6.9 \pm 1.3\%$. These values are very comparable to those from competitive hydroxylations of cyclohexane and perdeuterocyclohexane with iodosylbenzene catalysed by iron(III) porphyrins (k_H/k_D 7.7–9.0 [48]) and manganese(III) porphyrins (k_H/k_D 1.8–5.7 [48,49]) and support the hydrogen abstraction mechanism in Scheme 1. Changing the solvent from acetone to benzene, supporting the catalyst on SiSO₃[−] and carrying out the reaction in an inert atmosphere has no significant effect on the k_H/k_D values.

When the oxidations of pentane and cyclohexane in air were carried out in acetone, a new product, common to both reactions was obtained. Control reactions showed that this was not formed in the corresponding reactions in the other solvents, and that in acetone it was not found either in the absence of the substrate or when the oxidations were carried out under nitrogen. GC and GC–MS analysis of the product showed that its retention time and mass spectrum are identical to those of authentic 1-acetoxypropan-2-one. Its mechanism of formation remains unclear although we speculate it may involve the β -fragmentation of the alkoxy radical from the addition of propan-2-on-1-oxyl to acetone. The former presumably arises from the propan-2-on-1-yl radical and dioxygen. The requirement for the substrate and dioxygen may be to generate substrate peroxy radicals to abstract an α -hydrogen atom from acetone (Scheme 3). In



Scheme 3. Proposed mechanism for the formation of 1-acetoxypropan-2-one in manganese(III) porphyrin-catalysed oxidation of alkanes with iodosylbenzene using acetone as solvent.

support of this conclusion, the autoxidation of aliphatic ketones is known to show a strong regioselectivity for the α -position [50].

4. Conclusions

The results from this study on alkane oxidation by manganese(III) porphyrin/iodosylbenzene systems support an oxomanganese(V) porphyrin active oxidant which abstracts a hydrogen atom from the substrate to give a solvent-caged carbon radical and hydroxymanganese(IV) species. The alcohol to ketone product distribution but not the regio-selectivity of the reactions is determined by the partition of the carbon radicals between the cage and free solution. In air, the carbon radicals that escape the solvent cage are predominantly trapped by dioxygen to give peroxy radicals that react further to form ketones, whereas under nitrogen they form non-oxygenated products. Consequently the highest alcohol to ketone ratios are obtained from reactions under nitrogen.

With pentane as the substrate, the reactions show a large selectivity for secondary over primary C–H bonds but very little regio-selectivity between the two secondary positions. Attaching the manganese(III) porphyrins to supports affects the overall product yields but not the regio-selectivity of the oxidations.

The two major factors that control the alcohol to ketone ratio are dioxygen and the solvent's viscosity. Viscous solvents favour 'in cage' over 'out of cage' reactions and the absence of dioxygen minimises the yields of oxygenated products from alkyl radicals that escape the solvent cage.

The supported catalyst are simple to prepare and can be readily recovered for reuse at the end of the reaction. The best supported catalyst studied is **2**-SiSO₃[−] which gives moderate oxidation yields from pentane and cyclohexane.

Acknowledgments

This work has been supported by CAPES, CNPq and FAPESP. We are grateful to Dr. T.A. Dransfield for the MS analyses in York and Dr. L.A.B. de Moraes and D.B. Gianeti for MS analyses in Ribeirão Preto.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.molcata.2006.01.064.

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