Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Molecular Catalysis A: Chemical 201 (2003) 9–22

JOURNAL OF MOLECULAR CATALYSIS A: CHEMICAL

www.elsevier.com/locate/molcata

Oxidation of alkylaromatics with hydrogen peroxide catalysed by manganese(III) porphyrins in the presence of ammonium acetate

Susana L.H. Rebelo, Mário M.Q. Simões, M. Graça P.M.S. Neves, José A.S. Cavaleiro*

Department of Chemistry, University of Aveiro, 3810-193 Aveiro, Portugal

Received 28 October 2002; accepted 14 February 2003

Abstract

The oxidation of toluene (**1**), ethylbenzene (**2**) and cumene (**3**) with hydrogen peroxide, in the presence of several manganese(III) porphyrins with electron-withdrawing substituents, was studied using ammonium acetate as a co-catalyst. All products were characterised and their formation was justified by studying the oxidation of primary precursors, under the same conditions. The formation of the nitrate compounds was shown to be dependent on the presence of ammonium acetate. The oxidation of cumene and ethylbenzene afford products resulting from dehydrogenation reactions.

Keywords: Manganese(III) porphyrin; Oxidation; Hydrogen peroxide; Toluene; Ethylbenzene; Cumene; Ammonium acetate

1. Introduction

Oxidation of alkylbenzenes is an important transformation in chemical synthesis generally performed with corrosive, toxic or carcinogenic materials [1]. The desired products are usually obtained with low selectivity accompanied by ecologically dangerous by-products. The possibility of using metalloporphyrins as catalysts in the oxidation of these type of substrates has been proposed by several groups [2–6]. The products obtained are strongly dependent on the conditions used (catalyst, co-catalyst, oxidising agent and solvent).

We have recently shown that porphyrin manganese(III) complexes are efficient catalysts for the oxidation of aromatic terpenes (thymol, carvacrol and *p*-cymene) with H_2O_2 in the presence of NH_4AcO [7]. We now report the oxidation of toluene (**1**), ethylbenzene (**2**) and cumene (**3**) with H_2O_2 in the presence of catalysts **4** and **5** (Fig. 1).

Hydrogen peroxide was selected as the oxygen donor as a result of our interest [7–9] in developing oxidative catalytic systems that operate under environmentally friendly conditions [10]. For the required heterolytic cleavage of H_2O_2, we have chosen ammonium acetate as co-catalyst [11].

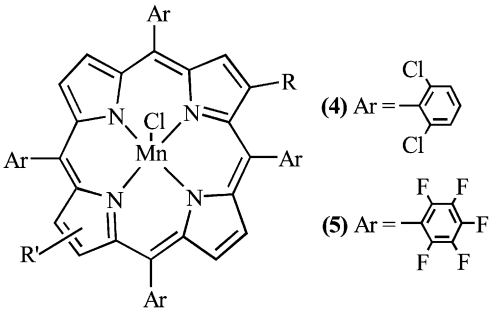
2. Results and discussion

2.1. Catalysts synthesis

The metalloporphyrins (**4** and **5**) free bases were prepared according to published procedures [12,13]. Metallation of the free bases leading to the formation of the complexes (**4** and **5**) was performed with $MnCl_2$ [14,15].

* Corresponding author: Fax: +351-2343-70084.
E-mail address: jcavaleiro@dq.ua.pt (J.A.S. Cavaleiro).

1381-1169/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S1381-1169(03)00149-3



(**4a**)	Mn(TDCPP)Cl	R=R'=H	
(**4b**)	Mn(β-NO_2TDCPP)Cl	R=NO_2	R'=H
(**4c**)	Mn(diβ-NO_2TDCPP)Cl	R=R'=NO_2	
(**5a**)	Mn(TF_5PP)Cl	R=R'=H	
(**5b**)	Mn(β-NO_2TF_5PP)Cl	R=NO_2	R'=H
(**5c**)	Mn(diβ-NO_2TF_5PP)Cl	R=R'=NO_2	

Fig. 1. Manganese(III) porphyrin complexes used in this study.

2.2. Oxidation of substrates

The arene oxidation reactions were carried out in acetonitrile at room temperature with addition of H_2O_2, in the presence of manganese(III) porphyrin and ammonium acetate. The reactions were followed by GC every 30 min and the addition of H_2O_2 was stopped when two successive GC analyses showed no more conversion of the substrate.

2.2.1. Oxidation of toluene (1)

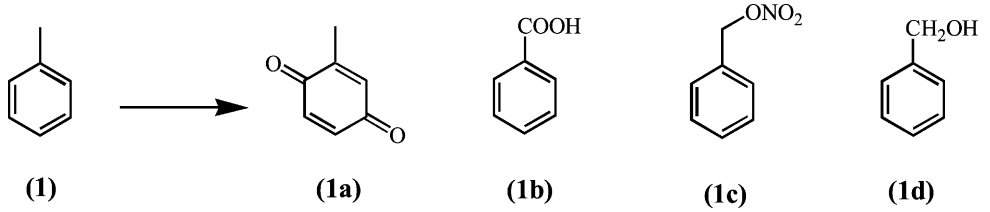
The GC analysis of the reaction mixture of toluene (**1**) showed that the main products were 2-methyl-1,4-benzoquinone (**1a**), benzoic acid (**1b**), benzyl nitrate (**1c**) and benzyl alcohol (**1d**) (Scheme 1 and Table 1). Trace quantities of benzaldehyde (**1e**), *o*-cresol (**1f**) and *p*-cresol (**1g**) were also detected.

The products **1b**, **1d**, **1e**–**g** were identified by comparing their mass spectra with other information available from a GC–MS data base and also by GC co-injection of authentic samples commercially available. Compound **1a** was identified by comparison with the GC behaviour and spectroscopic data of an authentic sample obtained by oxidation of *o*-cresol (**1f**) with H_2O_2 in the presence of a porphyrin catalyst (**4a**) and ammonium acetate as a co-catalyst (Scheme 2a).

Compound **1c** was extracted from the reaction mixture with $CHCl_3$ after adding an aqueous saturated solution of sodium carbonate. Purification by column chromatography on silica gel (*n*-hexane:CH_2Cl_2, 1:1) afforded **1c**. This compound was identified by mass spectrometry (Fig. 2) and NMR spectroscopy, as being benzyl nitrate. The structure of **1c** was confirmed by comparison of its GC behaviour and NMR profile with those of an authentic sample prepared by reaction of benzyl bromide with zinc nitrate [16].

In order to understand how the products are formed, the oxidations of benzyl alcohol (Scheme 2b) and benzaldehyde (Scheme 2c) with H_2O_2, under the same catalytic conditions, were investigated. It was observed that those oxidations only occur in the presence of a porphyrin catalyst and compound **1c** was not formed. This behaviour eliminates the possibility of **1d** and **1e** acting as primary intermediates leading to **1c** and indicates that the oxidation reactions of these substrates are also catalytic processes under the studied conditions.

It was also observed that compound **1c** is only formed in the presence of ammonium acetate. In fact, the oxidation of toluene using porphyrin **4a** as a catalyst and imidazole as co-catalyst did not afford compound **1c** (Table 1). However, this compound is



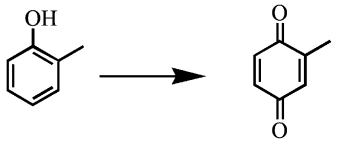
Scheme 1.

Table 1
Toluene oxidation reactions with H_2O_2 catalysed by Mn(III) porphyrins (**4** and **5**)[a]

Catalyst	*t* (h)	Conversion (%)[b]	Selectivity (%)[b]			
			1a	**1b**	**1c**	**1d**
No catalyst	9	0	0	0	0	0
Mn(TDCPP)Cl (**4a**)	6	31	4	49	37	7
Mn(β-NO_2TDCPP)Cl (**4b**)	7	68	5	58	33	3
Mn(diβ-NO_2TDCPP)Cl (**4c**)	8	62	4	86	8	2
Mn(TF_5PP)Cl (**5a**)	4.5	26	26	55	9	3
Mn(β-NO_2TF_5PP)Cl (**5b**)	4.5	16	45	42	0	0
Mn(diβ-NO_2TF_5PP)Cl (**5c**)	4.5	5	50	0	0	50
Mn(TDCPP)Cl—imidazole[c] (**4a**)	8.8	45	0	90	0	10
+$NaNO_2$[d] (**4a**)	6	24	2	48	36	8
+$NaNO_3$[d] (**4a**)	6	22	2	72	0	15

[a] Reaction conditions: the substrate **1**, 0.3 mmol; the catalyst, 3 μmol and ammonium acetate, 0.2 mmol were dissolved in acetonitrile (2.0 ml) and stirred at room temperature. Aqueous hydrogen peroxide (30% w/w) was diluted in acetonitrile (2:5) and added to the reaction mixture in 37.5 μl aliquots every 15 min.
[b] Based on gas chromatographic peak areas.
[c] The ammonium acetate was replaced by equimolar quantities of imidazole.
[d] Using Mn(TDCPP)Cl porphyrin and imidazole (0.2 mmol) as co-catalyst, 0.2 mmol of $NaNO_2$ or $NaNO_3$ were added to the reaction mixture.

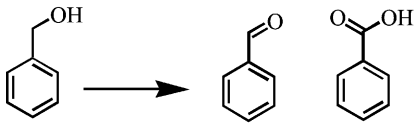
Scheme a



(1f) (1a)

			Selectivity
Catalyst	**Time**	**Conversion**	**(1a)**
(**4a**)	3.8 h	100 %	100 %
No catalyst	4 h	0 %	0 %

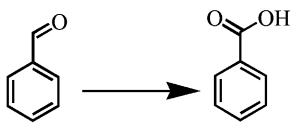
Scheme b



(1d) (1e) (1b)

			Selectivity	
Catalyst	**Time**	**Conversion**	**(1e)**	**(1b)**
(**4a**)	8.2 h	52 %	12 %	88 %
No catalyst	9 h	0 %	0 %	0 %

Scheme c



(1e) (1b)

			Selectivity
Catalyst	**Time**	**Conversion**	**(1b)**
(**4a**)	3 h	93 %	100 %
No catalyst	3 h	0 %	0 %

Scheme 2.

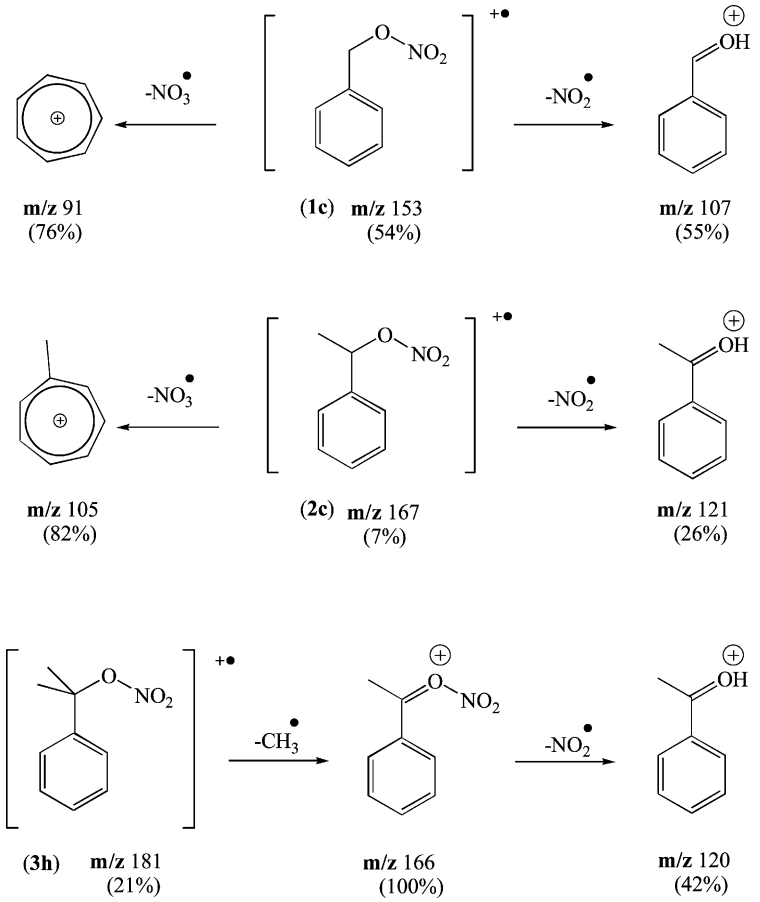


Fig. 2. Fragmentations observed in the mass spectra of the nitrated compounds **1c**, **2c** and **3h**, which are in agreement with the proposed structure. For compounds **1c** and **2c**, the more important fragmentations are the loss of $NO_2^{\bullet}$ or $NO_3^{\bullet}$ moieties and for compound **3h**, the losses of $CH_3^{\bullet}$ and $NO_2^{\bullet}$.

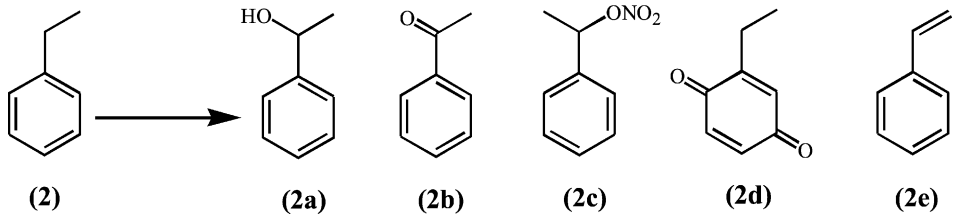
obtained in the presence of imidazole if sodium nitrite is added to the reaction mixture. With sodium nitrate, no insertion of the nitro group was observed. These results seem to indicate that NO_2^- or $NO_2^{\bullet}$ are intervening species in the formation of **1c**.

From Table 1, we can conclude that the manganese(III) porphyrin (**4b**) is a particularly good catalyst, in the presence of ammonium acetate, for the oxidation of this substrate, since we found an excellent conversion of 68% after 7 h of reaction. The best selectivity for benzoic acid (**1b**) is obtained with catalyst **4c**. On the other hand, the higher selectivity for benzyl nitrate (**1c**) is obtained with catalysts **4a** and **b**. It is interesting to note that, with porphyrins **5a–c**, the oxidation of the aromatic ring occurs to a greater extent subsequently giving compound **1a**.

2.2.2. Oxidation of ethylbenzene (2)

The GC–MS analyses of the ethylbenzene oxidation reactions have shown that mixtures are obtained. These oxidative transformations catalysed by the various metalloporphyrins gave rise to 1-phenylethanol (**2a**), acetophenone (**2b**), 1-phenylethyl nitrate (**2c**), 2-ethyl-1,4-benzoquinone (**2d**) and styrene (**2e**) (Scheme 3 and Table 2).

Products **2a**, **2b** and **2e** were confirmed by comparison with the GC behaviour of available standards. Compound **2d** was identified by considering its GC–MS results and by comparison with analytical data



Scheme 3.

(GC profile and NMR spectra) of an authentic sample of 2-ethyl-1,4-benzoquinone. This quinone was obtained in high yield by oxidation of 2-ethylphenol (**2f**) with H_2O_2/NH_4AcO in the presence of catalyst **4a** (Scheme 4a).

Compound **2c** was identified as 1-phenylethyl nitrate by considering its mass spectrum, which shows the same fragmentation pathway as benzyl nitrate (**1c**) (Fig. 2).

Previously, we have suggested that the nitration reaction product is related to the co-catalyst used, since no benzyl nitrate (**1c**) was formed during toluene oxidation in the presence of imidazole.

Ethylbenzene has faster reaction times than toluene and so a more extended study was carried out in order to understand the influence of the co-catalyst on the oxidation process. Ammonium acetate performance was compared with four other potential co-catalysts and Mn(β-NO_2TDCPP)Cl (**4b**) was chosen as the catalyst, since it gives rise to the highest conversion of **2** and the best selectivity for the nitro compound **2c**.

From the co-catalysts referred to in the literature for the activation of hydrogen peroxide in the presence of metalloporphyrins, the best results seem to be obtained by buffering substances or combinations of acids and bases, i.e. ammonium acetate [11], imidazole [4], pyridine plus benzoic acid [17,18] (but evidence of pyridine oxidation was also observed [19]). Also the pH of the reaction mixture was revealed to be a key factor in the oxidation reactions carried out in aqueous media with iron phthalocyanines [20]. Based on these facts, the co-catalysts chosen for these studies were ammonium acetate, imidazole, sodium acetate, a mixture of equimolar quantities of sodium acetate and acetic acid and a mixture of equimolar quantities of sodium acetate and benzoic acid (Table 3). The formation of the nitrated product was observed only with ammonium acetate, which indicates that the nitrate group is derived from the ammonium ion.

To investigate the insertion of the nitro group in the benzylic position of ethylbenzene, two other ethylbenzene oxidation reactions were performed, using imidazole as co-catalyst and adding equivalent quantities of sodium nitrite or nitrate to the reaction mixtures. The selectivity for the nitrated compound **2c**, changed from 0% with imidazole alone to 8% with imidazole and sodium nitrite. No nitrated compound was observed when imidazole and sodium nitrate were used

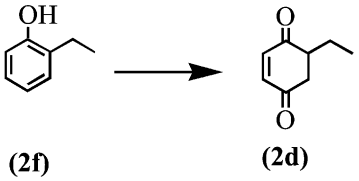
Table 2
Ethylbenzene oxidation reactions with H_2O_2 catalysed by Mn(III) porphyrins (**4** and **5**)[a]

Catalyst	*t* (h)	Conversion (%)[b]	Selectivity (%)[b]				
			2a	**2b**	**2c**	**2d**	**2e**
No catalyst	10.0	0	0	0	0	0	0
Mn(TDCPP)Cl (**4a**)	6.5	64	21	75	4	0	0
Mn(β-NO_2TDCPP)Cl (**4b**)	5.5	66	20	66	7	1	6
Mn(TF_5PP)Cl (**5a**)	3.2	57	25	65	3	4	2
Mn(β-NO_2TF_5PP)Cl (**5b**)	4	10	32	68	0	0	0

[a] Reaction conditions: the substrate **2**, 0.3 mmol; the catalyst, 3 μmol and ammonium acetate, 0.2 mmol were dissolved in acetonitrile (2.0 ml) and stirred at room temperature. Aqueous hydrogen peroxide (30% w/w) was diluted in acetonitrile (2:5) and added to the reaction mixture in 37.5 μl aliquots every 15 min.

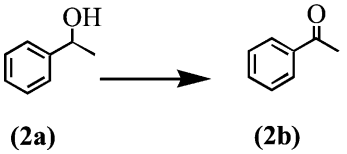
[b] Based on gas chromatographic peak areas.

Scheme a



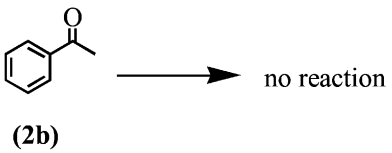
Catalyst	Time	Conversion	Selectivity (2d)
(**4a**)	2.5 h	100 %	100 %
No catalyst	3 h	0 %	0 %

Scheme b



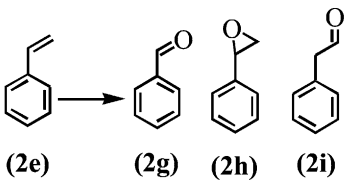
Catalyst	Time	Conversion	Selectivity (2b)
(**4a**)	2.5 h	60 %	100 %
No catalyst	2.5 h	0 %	0 %

Scheme c



Catalyst	Time	Conversion
(**4a**)	5 h	0 %

Scheme d



Catalyst	Time	Conversion	Selectivity (2g)	(2h)	(2i)
(**4a**)	2 h	100 %	traces	94 %	6 %
No catalyst	2 h	0 %	0 %	0 %	0 %

Scheme 4.

instead. These results are similar to those obtained in the toluene oxidation experiments and reinforce the idea that the nitrite moiety interferes with the formation of nitrated compounds.

From the results of Table 3, it is particularly interesting to note the great improvement in the conversion of ethylbenzene, comparing the reaction using sodium acetate alone (21%) with that in which the sodium acetate/acetic acid mixture was used (83%). The pH of the reaction medium seems to be important for the efficiency of the process, since the best conversions are obtained with buffering co-catalysts (ammonium acetate, imidazole, sodium acetate/acetic acid or sodium acetate/benzoic acid). The co-catalyst sodium acetate/benzoic acid showed the best performance. Further studies with such system are in progress.

The oxidation of 1-phenylethanol (**2a**), acetophenone (**2b**), styrene (**2e**) and 2-ethylphenol (**2f**) with H_2O_2 under the same catalytic conditions used for ethylbenzene (**2**) were also investigated (Scheme 4). It was observed that the oxidation of **2a** only affords **2b** (Scheme 4b). This behaviour excludes the possibility of styrene (**2e**) arising from dehydration of the alcohol (**2a**). Products resulting from further oxidation of

Table 3
Influence of the different co-catalysts used in catalytic oxidation of ethylbenzene with H_2O_2 in the presence of metalloporphyrin **4b**[a]

Co-catalyst	*t* (h)	Conversion (%)[b]	Selectivity (%)[b]				
			2a	**2b**	**2c**	**2d**	**2e**
Ammonium acetate	5.5	66	20	66	7	1	6
Imidazole	8.5	70	17	81	0	1	1
Sodium acetate	7.5	21	9	91	0	0	0
Sodium acetate + acetic acid	7.5	83	9	87	0	3	1
Sodium acetate + benzoic acid	8.5	92	12	88	0	0	0
Imidazole + $NaNO_2$[c]	7.0	76	18	72	8	0	1
Imidazole + $NaNO_3$[c]	6.8	74	25	74	0	0	1

[a] Reaction conditions: the substrate **2**, 0.3 mmol; the catalyst, 3 μmol and the co-catalyst, 0.2 mmol were dissolved in acetonitrile (2.0 ml) and stirred at room temperature. Aqueous hydrogen peroxide (30% w/w) was diluted in acetonitrile (2:5) and added to the reaction mixture in 37.5 μl aliquots every 15 min.
[b] Based on gas chromatographic peak areas.
[c] Using imidazole (0.2 mmol) as co-catalyst, 0.2 mmol of $NaNO_2$ or $NaNO_3$ were added to the reaction mixture.

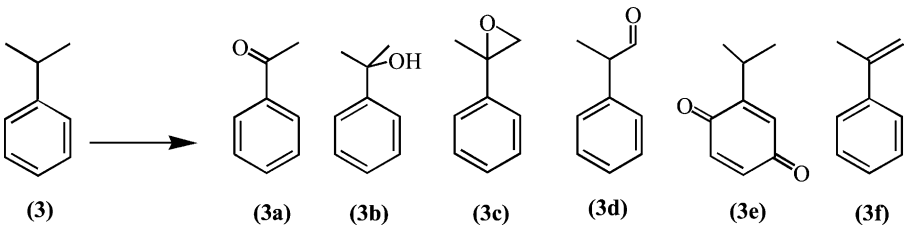
2e were not detected in the oxidation of ethylbenzene (Scheme 4d) and acetophenone (**2b**) did not react under these conditions (Scheme 4c). Moreover, these results also show that the oxidation reactions of **2a**, **2e** and **2f** are catalytic processes, since no oxidation products were observed without the presence of the metalloporphyrin catalyst. We can also conclude that none of these compounds is a precursor of 1-phenylethyl nitrate (**2c**).

As far as the efficiency of the catalysts is concerned, we can observe from Table 2 that acetophenone (**2b**) is always the major product from the oxidation of **2** with all four catalysts. The best conversion percentages were obtained with catalysts of type **4**. Porphyrin **4a** is more selective than **4b**, since no styrene (**2e**) or aromatic ring oxidation products were detected.

2.2.3. Oxidation of cumene (3)

The six compounds obtained in the oxidation reactions of cumene (Scheme 5, Table 4) were identified by GC–MS analysis as being acetophenone (**3a**), 2-phenyl-2-propanol (**3b**), α-methylstyrene epoxide (**3c**), 2-phenylpropanal (**3d**), 2-isopropyl-1,4-benzoquinone (**3e**) and α-methylstyrene (**3f**). Trace quantities of 2-isopropylphenol (**3g**) and α,α-dimethylbenzyl nitrate (**3h**) were also observed. Compounds **3a**, **3b**, **3f** and **3g** were also confirmed by comparison with GC analyses of available standards.

In this case, we also tried to clarify the formation of the oxidation products obtained, by studying the oxidation of the potential intermediates **3b**, **3f**, **3g** and **3i**, under the same catalytic conditions used for the reactions of cumene (Scheme 6). Compound **3e** was obtained in high yield by oxidation of **3g** with H_2O_2/NH_4AcO in the presence of catalyst **4a** (Scheme 6a), and was isolated by column chromatography and characterised by ^1H NMR and GC–MS. No product was obtained from the oxidation of 2-phenyl-2-propanol (**3b**), thus excluding the possibility of α-methylstyrene (**3f**) arising from the dehydration of alcohol (**3b**) obtained during the oxidation of cumene. This result also



Scheme 5.

Table 4
Cumene oxidation reactions with H_2O_2 catalysed by Mn(III) porphyrins (**4** and **5**)[a]

Catalyst	t (h)	Conversion (%)[b]	Selectivity (%)[b]					
			3a	**3b**	**3c**	**3d**	**3e**	**3f**
No catalyst	10.0	0	0	0	0	0	0	0
Mn(TDCPP)Cl (**4a**)	6.8	42	18	65	17	0	0	0
Mn(β-NO_2TDCPP)Cl (**4b**)	10.0	41	18	56	16	3	3	4
Mn(TF_5PP)Cl (**5a**)	3.0	52	12	65	16	2	3	2
Mn(β-NO_2TF_5PP)Cl (**5b**)	7.0	13	16	60	13	1	0	10

[a] Reaction conditions: the substrate **3**, 0.3 mmol, the catalyst, 3 μmol and ammonium acetate, 0.2 mmol were dissolved in acetonitrile (2.0 ml) and stirred at room temperature. Aqueous hydrogen peroxide (30% w/w) was diluted in acetonitrile (2:5) and added to the reaction mixture in 37.5 μl aliquots every 15 min.
[b] Based on gas chromatographic peak areas.

eliminates the possibility of **3b** being a precursor of acetophenone (**3a**) (Scheme 6b). The oxidation of α-methylstyrene (**3f**), under our catalytic conditions, afforded **3a**, **3c** and **3d** (Scheme 6c). This result shows that these products, also obtained during the oxidation of cumene, may arise from the further oxidation of α-methylstyrene (**3f**). The possibility that α-methylstyrene (**3f**) could have been formed from the dehydration of 2-phenyl-1-propanol (**3i**) was excluded. No α-methylstyrene (**3f**) was detected during the oxidation of **3i** (Scheme 6d). Although this alcohol (**3i**) was never detected in the oxidation reactions of cumene, we cannot totally exclude the possibility that this compound is the primary precursor of acetophenone (**3a**) and 2-phenylpropanal (**3d**).

It is worth noting that for substrate **3**, α,α-dimethylbenzyl nitrate (**3h**) was only detected in very low yield; its identification was based on GC–MS spectrum, which shows a mass fragmentation pathway similar to the other nitrates (**1c** and **2c**) (Fig. 2).

From these results and from Table 4, we can conclude that cumene oxidation occurs by two main oxidation pathways: the benzylic hydroxylation pathway with 56–65% selectivity for product **3b** and the dehydrogenation pathway leading to **3f**, which is then oxidised to **3a**, **3c** and **3d**, with 32–41% selectivity for the total amount of these products.

The best catalytic performance in the oxidation reactions of **3** was achieved with porphyrin **5a**, whereas substrates **1** and **2** gave rise to higher conversions with type **4** porphyrins. When *p*-cymene oxidation was studied in the presence of these type of catalysts [7], a similar result was obtained. Indeed, porphyrin **5** improved the selectivity for the oxidation of the more inaccessible tertiary benzylic position of *p*-cymene, whereas porphyrin **4** was more selective for the oxidation of the primary benzylic position.

2.3. Mechanistic considerations

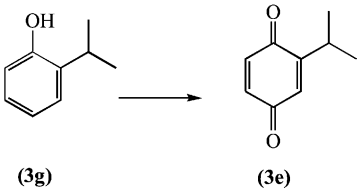
It is possible to elaborate a general reaction pathway (Scheme 7) consistent with the observations made in the oxidation of arenes (**1**–**3**) with manganese(III) porphyrins. The various pathways are dependent on the manganese(III) porphyrin used and if the substrates have primary, secondary or tertiary benzylic positions.

The importance of the pH reaction mixture on the efficiency of the oxidation process is confirmed by the results in Table 3. The observed efficiency for buffering co-catalysts can be explained by the characteristics of the hydrogen peroxide activation process [21], which is accelerated by successive basic and acidic catalysis (Scheme 8).

Path 1, a hydroxylation reaction catalysed by metalloporphyrins, has a mechanism that has been fully discussed [22,23]. Our results also show that paths 1.1 and 1.2 are catalytic processes; the reactions involved only occur in the presence of a metalloporphyrin catalyst. Campestrini and co-workers [24,25] also referred to the fact that the oxidation of benzylic alcohols by oxo-manganese species are catalytic processes and appear to proceed by a dehydrogenation mechanism, instead of an alcohol hydroxylation followed by the loss of water leading to a ketone.

Although in all cases the oxidation takes place mainly in the benzylic positions, porphyrin (**5**) shows a higher preference for the oxidation of the aromatic

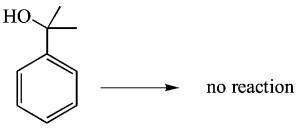
Scheme a



(3g) (3e)

Catalyst	Time	Conversion	Selectivity (2d)
(**4a**)	3 h	93 %	100 %
No catalyst	3 h	0 %	0%

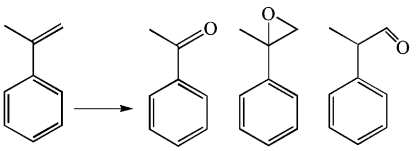
Scheme b



(3b)

Catalyst	Time	Conversion
(**4a**)	5 h	0 %

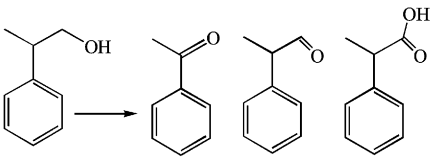
Scheme c



(3f) (3a) (3c) (3d)

Catalyst	Time	Conversion	Selectivity (3a)	(3c)	(3d)
(**4a**)	1 h	100 %	6 %	90 %	4 %
No catalyst	2.5 h	0 %	0 %	0 %	0 %

Scheme d



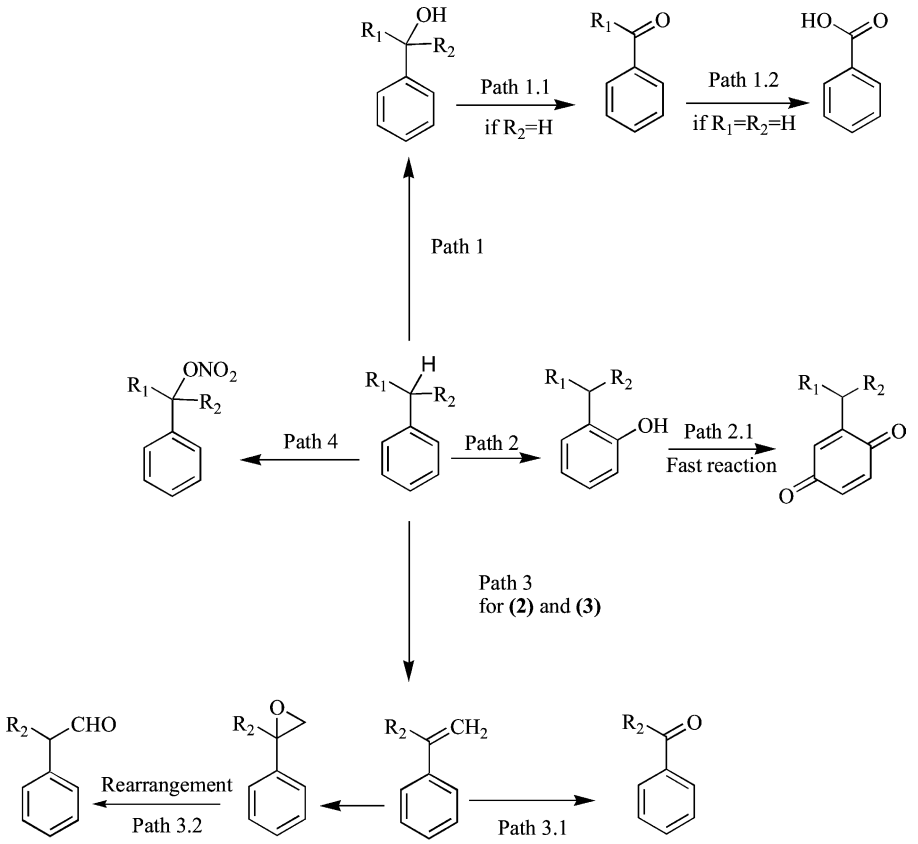
(3i) (3a) (3d) (3j)

Catalyst	Time	Conversion	Selectivity (3a)	(3d)	(3j)
(**4a**)	2 h	22 %	61 %	2 %	15 %
(**5a**)	3.5 h	27 %	80 %	trace	20 %

Scheme 6.

ring than porphyrin (**4**), which affords quinones (path 2). Based on the fact that phenols were detected during the reaction course and quinones are easily and selectively obtained by oxidation of alkylphenols with H_2O_2, catalysed by Mn(III) porphyrins [7], we suggest that the hydroxylation of the aromatic ring is the first and most difficult step (path 2). Phenol is then selectively and more easily oxidised to the corresponding quinone (path 2.1).

For ethylbenzene (**2**) and cumene (**3**), that undergo path 3, it was proved that these reactions do not proceed via an alcohol intermediate and are oxidative dehydrogenation processes catalysed by manganese(III) porphyrins. Our observations are supported by dehydrogenation reactions observed with cytochrome P450 [26] and with a soluble methane mono-oxygenase (MMO), a non-haem containing enzyme [27]. These compounds are capable of catalysing dehydrogenation



Toluene **(1)** $R_1 = R_2 = H$

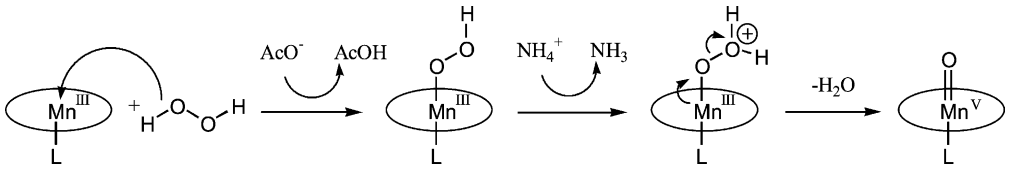
Ethylbenzene **(2)** $R_1 = CH_3$; $R_2 = H$

Cumene **(3)** $R_1 = R_2 = CH_3$

Scheme 7.

reactions, in addition to hydroxylation and epoxidation reactions of certain substrates, such as ethylbenzene and cyclohexadienes. The mechanism has been postulated to begin with abstraction of an hydrogen atom and after that, there might be a competition between oxygen rebound and abstraction of what is formally a second hydrogen atom [26].

Path 3.1 is especially important in oxidation reactions involving cumene, and where acetophenone is one of the major products. Previous work on tertiary



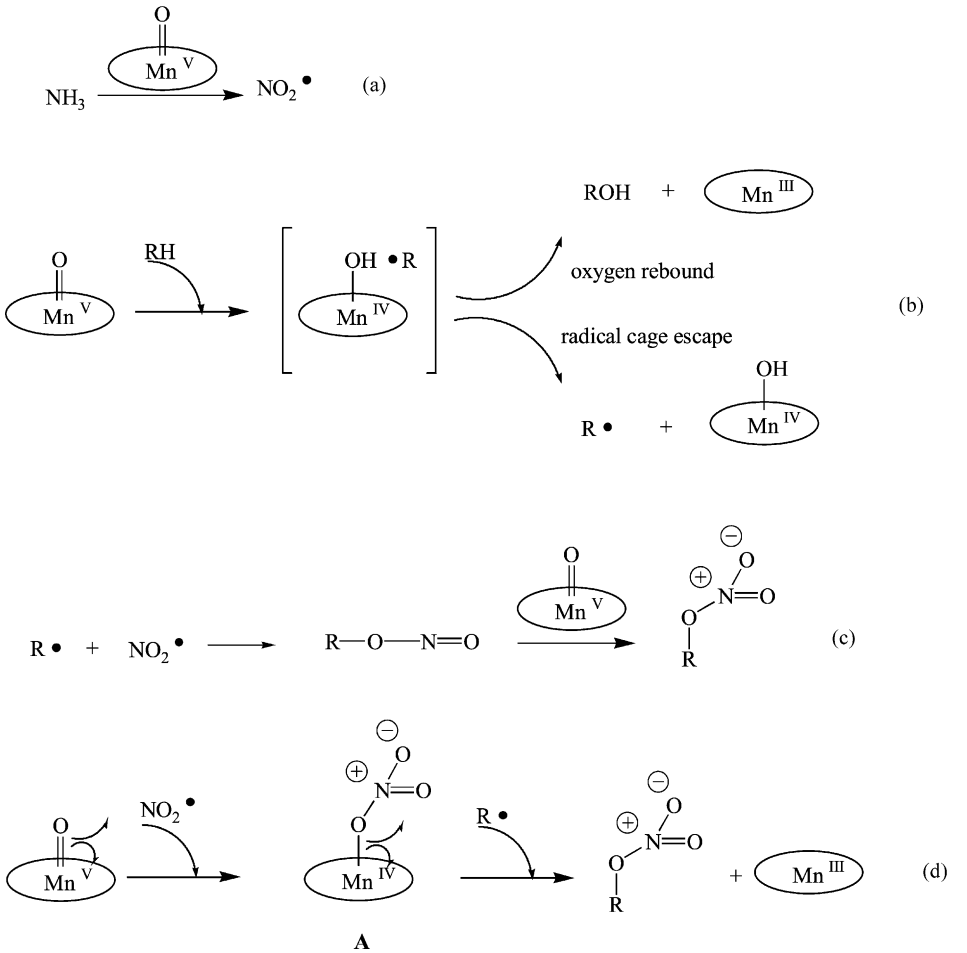
Scheme 8.

alcohol oxidation, catalysed by metalloporphyrins, indicated that C–H cleavage leading to ketones could compete with C–C cleavage [28,29]. Under our conditions, acetophenone does not proceed from the oxidation of 2-phenyl-2-propanol (**3b**) (Scheme 6b), but it is obtained as a product in the α-methylstyrene oxidation (**3f**) (Scheme 6c). It is therefore, likely that acetophenone is produced through oxidative double bond cleavage. Such a transformation has been described in the oxidation of styrene catalysed by MnTPPCl leading to benzaldehyde [30]. Also the oxidation of styrene and α-methylstyrene, with iodosylbenzene catalysed by *trans*-dioxoosmium(VI) porphyrins, gave as major products benzaldehyde and acetophenone, respectively [31].

The aldehydes, **2g** and **3d** obtained via path 3.2 can be primary oxidation products of the corresponding alkenes, as proposed by Collman et al. [32]. A pinacol type rearrangement [33] or a simple rearrangement of the terminal epoxide could also justify the formation of these type of compounds.

Finally, the formation of nitrate derivatives (path 4, Scheme 7) seems to depend on the presence of the NH_4^+/NH_3 pair in the reaction mixture.

It is known that primary aromatic amines can be oxidised to the corresponding nitro derivatives by *t*-butyl hydroperoxide, in the presence of Fe(III) or Mn(III) tetraarylporphyrins [34] (ammonia is likely to be oxidised to nitrogen dioxide (Scheme 9a)).



Scheme 9.

It has also been postulated that after hydrogen abstraction from a saturated substrate by a high valent oxo-complex, a radical cage can escape and compete with an oxygen rebound mechanism [35] (Scheme 9b).

The radical combination of the $NO_2^{\bullet}$ with $R^{\bullet}$, followed by oxidation of the resultant alkyl nitrite can afford the final alkyl nitrate (Scheme 9c) or, more likely, $NO_2^{\bullet}$ in combination with the oxomanganese porphyrin, affords the intermediate A, which can react with freely diffusing alkyl radicals, and produce the nitrated compound (Scheme 9d).

3. Experimental

3.1. General details

^1H and ^{13}C NMR spectra were recorded in $CDCl_3$, using a Bruker DRX 300 at 300.13 and 75.47 MHz, respectively. The chemical shifts are expressed in δ (ppm) values relative to tetramethylsilane (TMS). Preparative thin layer chromatography (TLC) was carried out on silica gel plates (Riedel de Haën silica gel 60 DGF_{254}). Column chromatography was also performed on silica gel (Merck silica gel 60, 70–230 mesh). Mass spectra were obtained using a VG Autospec Q mass spectrometer. GC–MS analyses were performed using a Finnigan Trace GC/MS (Thermo Quest CE Instruments) using helium as the carrier gas (35 cm/s). GC-FID was performed using a Varian Star 3400CX chromatograph and hydrogen as the carrier gas (55 cm/s). In both cases fused silica Supelco capillary columns SPB-5 (30 m × 0.25 mm i.d.; 0.25 μm film thickness) were used. The chromatographic conditions were as follows: initial temperature, 70 °C, during 4 min; temperature rate, 20 °C/min; final temperature, 220 °C; injector temperature, 220 °C; detector temperature, 230 °C (reactions with toluene) and initial temperature, 80 °C, during 1 min; temperature rate, 7 °C/min; final temperature, 200 °C; injector temperature, 220 °C; detector temperature, 230 °C (reactions with ethylbenzene and cumene). Aliquots were withdrawn from the reaction mixture and injected directly into the injector. The percentages of each compound in the reaction mixtures were estimated directly from the corresponding gas chromatographic peak areas.

Hydrogen peroxide (30 wt.% solution in water), benzaldehyde, benzyl alcohol, acetophenone and toluene were purchased from Riedel de Haën. Ethylbenzene, cumene, *o*-cresol, *p*-cresol, 2-ethylphenol, 2-isopropylphenol, styrene, α-methylstyrene, 2-phenyl-2-propanol and 2-phenyl-1-propanol were purchased from Aldrich. (±)-1-Phenylethanol was purchased from Fluka. All other chemicals and solvents used herein were obtained from commercial sources and used as received or distilled and dried using standard procedures. Light petroleum was the fraction of bp 40–60 °C.

3.2. General oxidation procedure

In a typical experiment, the substrate **1**–**3** (0.3 mmol), the catalyst (3 μmol) and ammonium acetate (0.2 mmol) were dissolved in acetonitrile (2 ml) and stirred at room temperature. Aqueous hydrogen peroxide (30% w/w) diluted in acetonitrile (2:5) was added to the reaction mixture in 37.5 μl aliquots every 15 min. The reactions were followed by GC analysis and stopped when the product yields remained constant after two successive GC analyses. The reaction mixture was then poured into water and extracted with dichloromethane. The organic phase was dried with anhydrous sodium sulphate and concentrated in a rotary evaporator. The mixtures were separated by chromatography on a silica gel column, eluting with a mixture of dichloromethane:light petroleum (1:1). The content of the various fractions was identified by GC analysis. The NMR spectra were obtained after drying the pure compound extracts in a rotary evaporator at 50 °C for 30 min.

3.2.1. Experiments with different co-catalysts

Oxidation of toluene was carried out under the conditions described in Section 3.2 using porphyrin **4a** and replacing ammonium acetate by equimolar quantities of imidazole.

Oxidation of ethylbenzene was also carried out under the conditions described in Section 3.2 using porphyrin **4b** and replacing ammonium acetate by equimolar quantities of imidazole, sodium acetate, a mixture of equimolar quantities of sodium acetate and acetic acid or a mixture of equimolar quantities of sodium acetate and benzoic acid.

3.2.2. Experiments with imidazole and sodium nitrite or nitrate

Toluene and ethylbenzene were also oxidised using imidazole (0.2 mmol) as co-catalyst and 0.2 mmol of $NaNO_2$ or $NaNO_3$ were added to the reaction mixture.

3.3. Synthesis of benzyl nitrate

$Zn(NO_3)_2{\cdot}6H_2O$ (2.34 mg, 8 mmol) was added to benzyl bromide (1 ml, 8 mmol) dissolved in acetonitrile (1 ml), and the mixture was stirred for 24 h at room temperature. GC analysis revealed 75% conversion and 80% selectivity for benzyl nitrate (**1c**). The reaction mixture was washed with aqueous saturated sodium hydrogenocarbonate solution and extracted with $CHCl_3$. The organic phase was passed through anhydrous sodium sulphate and concentrated in vacuum. The extract was chromatographed through a silica gel column using $CHCl_3$:*n*-hexane (1:1) as eluent. The NMR spectrum was obtained after drying the compound in a rotary evaporator at 50 °C for 30 min.

3.4. Synthesis of 2-substituted-1,4-benzoquinones

Quinones **1a**, **2d** and **3e** were obtained following the general oxidation procedure but using the respective 2-alkylphenols as substrates and 1 μmol of catalyst **4a**.

*3.4.1. 2-Methyl-1,4-benzoquinone (**1a**)*

^{1}H NMR δ: 2.07 (d, 3H, H-7, *J* 1.5 Hz), 6.62–6.64 (m, 1H, H-3), 6.72 (dd, 1H, H-5, *J* 2.2 and 10.1 Hz), 6.77 (d, 1H, H-6, *J* 10.1 Hz). MS (EI) *m*/*z* (rel. int. %): 122 ($M^{\bullet+}$, 52), 94 (95), 82 (70), 68 (45), 66 (63), 65 (23), 54 (100).

*3.4.2. Benzyl nitrate (**1c**)*

^{1}H NMR δ: 5.43 (s, 2H, H-7), 7.41 (s, 5H, H-2,3,4,5,6). ^{13}C NMR δ: 31.0 (C-7), 128.8 (C-4), 129.1 (C-3,5), 129.5 (C-6,2), 132.1 (C-1). MS (EI) *m*/*z* (rel. int. %): 153 ($M^{\bullet+}$, 54), 107 (55), 106 (47), 105 (65), 91 (76), 79 (62), 78 (40), 77 (100).

*3.4.3. 1-Phenylethyl nitrate (**2c**)*

MS (EI) *m*/*z* (rel. int. %): 167 ($M^{\bullet+}$, 7), 121 (26), 105 (82), 78 (22), 77 (100).

*3.4.4. 2-Ethyl-1,4-benzoquinone (**2d**)*

^{1}H NMR δ: 1.15 (t, 3H, H-8, *J* 7.4 Hz), 2.47 (dq, 2H, H-7, *J* 1.7 and 7.4 Hz), 6.56–6.58 (m, 1H, H-3), 6.72 (dd, 1H, H-5, *J* 2.2 and 10.1 Hz), 6.77 (d, 1H, H-6, *J* 10.1 Hz). ^{13}C NMR δ: 11.5 (C-8), 22.1 (C-7), 131.6 (C-3), 136.2 and 136.8 (C-5,6), 150.8 (C-2), 187.5 and 187.9 (C-1,4). MS (EI) *m*/*z* (rel. int. %) 136 ($M^{\bullet+}$, 86), 123 (23), 108 (100), 107 (75), 82 (83), 80 (45), 79 (92).

*3.4.5. 2-Isopropyl-1,4-benzoquinone (**3e**)*

^{1}H NMR δ: 1.14 (d, 6H, H-8,9), 3.04 (dh, 1H, H-7, *J* 1.1 and 6.7), 6.55 (dd, 1H, H-3, *J* 1.1 and 2.2 Hz), 6.71 (dd, 1H, H-5, *J* 2.2 and 10.0 Hz), 6.76 (d, 1H, H-6, *J* 10.0 Hz). MS (EI) *m*/*z* (rel. int.) 150 ($M^{\bullet+}$, 57), 137 (27), 134 (24), 122 (79), 107 (63), 94 (27), 82 (29), 81 (18).

*3.4.6. α-Methylstyryl nitrate (**3h**)*

MS (EI) *m*/*z* (rel. int.) 181 ($M^{\bullet+}$, 21), 166 (100), 120 (42), 91 (24), 77 (9).

4. Conclusions

The oxidation of toluene (**1**), ethylbenzene (**2**) and cumene (**3**) with hydrogen peroxide in the presence of several manganese(III) porphyrins was studied, under mild conditions, using ammonium acetate as co-catalyst. The best conversions for **1** and **2** were observed with type **4** porphyrins containing electron-withdrawing groups in the β-pyrrolic positions, **4b** and **4c**. For **3**, the best conversion was observed with porphyrin **5a**.

All products obtained in the oxidation of **1** were identified and we suggest that compound **1b** could be formed by the catalytic oxidation of the corresponding alcohol and aldehyde. The formation of **1c** is dependent on the presence of an ammonium ion and is also obtained with sodium nitrite using imidazole as co-catalyst. With this substrate, the hydroxylation of the aromatic ring occurred preferentially with type **5** porphyrins.

The oxidation of **2** with all the catalysts used afforded acetophenone as the main product. The oxidation of alcohol **2a** was shown to be a catalytic process and the products resulting from the hydroxylation of the aromatic ring, nitration of the benzylic position and dehydrogenation of alkylgroups, were obtained in minor amounts.

We have shown that the oxidation of **3** afforded products resulting mainly from the hydroxylation

of the benzylic position, **3b** and from dehydrogenation (**3a**, **3c**, **3d**, **3f**). The catalytic oxidation of α-methylstyrene (**3f**) afforded compounds **3a**, **3c**, **3d**; **3f** is then a potential primary intermediate leading to these compounds in cumene's oxidation.

Acknowledgements

Thanks are due to the University of Aveiro and Fundação para a Ciência e a Tecnologia (FCT) for funding the Organic Chemistry Research Unit. S.L.H. Rebelo also thanks FCT for a Ph.D. grant. We also thank Prof. Graça Santana Marques of University of Aveiro for the mass spectra analyses.

References

[1] M. Hudlický, Oxidations in Organic Chemistry, American Chemical Society, Washington, 1990, p. 99.
[2] S. Evans, J.R. Lindsay Smith, J. Chem. Soc., Perkin Trans. 2 (2000) 1541.
[3] J.F. Bartoli, V. Mouries-Mansuy, K. Le Barch-Ozette, M. Palacio, P. Battioni, D. Mansuy, J. Chem. Soc., Chem. Commun. (2000) 827.
[4] P. Battioni, J.P. Renaud, J.F. Bartoli, M. Reina-Artiles, M. Fort, D. Mansuy, J. Am. Chem. Soc. 110 (1988) 8462.
[5] E. Baciocchi, O. Lanzalunga, A. Lapi, Tetrahedron Lett. 36 (1995) 3547.
[6] D. Mohajer, A. Rezaeifard, Tetrahedron Lett. 43 (2002) 1881.
[7] R.R.L. Martins, M.G.P.M.S. Neves, A.J.D. Silvestre, A.M.S. Silva, J.A.S. Cavaleiro, J. Mol. Catal. A: Chem. 137 (1999) 41.
[8] J.A.S. Cavaleiro, G.M.S.F.C. Nascimento, M.G.P.M.S. Neves, M.T. Pinto, A.J.D. Silvestre, M.G.H. Vicente, Tetrahedron Lett. 37 (1996) 1893.
[9] R.R.L. Martins, M.G.P.M.S. Neves, A.J.D. Silvestre, M.M.Q. Simões, A.M.S. Silva, A.C. Tomé, J.A.S. Cavaleiro, P. Tagliatesta, C. Crestini, J. Mol. Catal. A: Chem. 172 (2001) 33.
[10] W.R. Sanderson, Pure Appl. Chem. 72 (2000) 1289.
[11] A. Thellend, P. Battioni, D. Mansuy, J. Chem. Soc., Chem. Commum. (1994) 1035.
[12] A.M.A.R. Gonçalves, J.M.T.B. Varejão, M.M. Pereira, J. Heterocycl. Chem. 28 (1991) 635.
[13] A. Sen, V. Krishnan, Tetrahedron Lett. 37 (1996) 5921.
[14] J.W. Buchler, in: D. Dolphin (Ed.), The Porphyrins, vol. 1, Academic Press, New York, 1978, p. 398 and references cited therein.
[15] A.D. Adler, F.R. Longo, F. Kampes, J.J. Kim, Inorg. Nucl. Chem. 32 (1970) 2443.
[16] R.G. Coombes, in: D. Barton, W.D. Ollis (Eds.), Comprehensive Organic Chemistry: The Synthesis and Reactions of Organic Compounds, vol. 2, Pergamon Press, Oxford, 1979, p. 360.
[17] A.M.A.R. Gonçalves, A.C. Serra, J. Porphyrins Phthalocyanines 4 (2000) 598.
[18] A.M.A.R. Gonçalves, A.C. Serra, J. Mol. Catal. A: Chem. 168 (2001) 25.
[19] T. Zeng, D. Richardson, Tetrahedron Lett. 36 (1995) 837.
[20] A. Hadash, A. Sorokin, A. Rabion, B. Meunier, New J. Chem. (1998) 45.
[21] I.D. Cunningham, T.N. Danks, K.T.A. O'Connel, P.W. Scott, J. Chem. Soc., Perkin Trans. 2 (1999) 2133.
[22] Ortiz de Montellano (Ed.), Cytochrome P450: Structure, Mechanism and Biochemistry, Plenum Press, New York, 1986.
[23] B. Meunier, A. Robert, G. Pratviel, J. Bernardou, in: K.M. Kadish, K.M. Smith, R. Guilard (Eds.), The Porphyrin Handbook, vol. 4, Academic Press, New York, 2000 (Chapter 31).
[24] A. Cagnina, S. Campestrini, F. Di Furia, P. Ghiotti, J. Mol. Catal. A: Chem. 130 (1998) 221.
[25] S. Campestrini, A. Cagnina, J. Mol. Catal. A: Chem. 150 (1999) 77.
[26] F.P. Guengerich, Chem. Res. Toxicol. 14 (2001) 611.
[27] Y. Jin, J.D. Lipscomb, J. Biol. Inorg. Chem. 6 (2001) 717.
[28] K. Wietzerbin, J. Bernadou, B. Meunier, Eur. J. Inorg. Chem. (1999) 1467.
[29] E. Baciocchi, S. Belvedere, Tetrahedron Lett. 39 (1998) 4711.
[30] J.-P. Renaud, P. Battioni, J.F. Bartoli, D. Mansuy, J. Chem. Soc., Chem. Commum. (1985) 888.
[31] Z. Gross, A. Mahammed, J. Mol. Catal. A: Chem. 142 (1999) 367.
[32] J.P. Collman, T. Kodadek, J.I. Brauman, J. Am. Chem. Soc. 108 (1986) 2588.
[33] J.T. Groves, T.S. Myers, J. Am. Chem. Soc. 105 (1983) 5791.
[34] S. Tollari, D. Vergani, S. Banfi, F. Porta, J. Chem. Soc., Chem. Commun. (1993) 442.
[35] J.R. Lindsay Smith, in: R.A. Sheldon (Ed.), Metalloporphyrins in Catalytic Oxidations, Marcel Dekker, New York, 1994, p. 355.