

# Efficient Stereoselective Oxygenation of Alkanes by Peroxyacetic Acid or Hydrogen Peroxide and Acetic Acid Catalysed by a Manganese(IV) 1,4,7-Trimethyl-1,4,7-triazacyclononane Complex

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Received 2 April 1998; accepted 27 April 1998

## Abstract

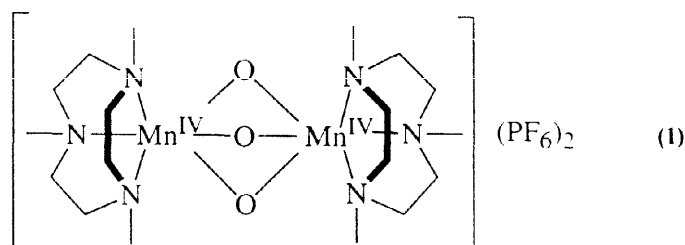
The dinuclear manganese complex  $[\text{LMn}^{\text{IV}}(\text{O})_3\text{Mn}^{\text{IV}}\text{L}](\text{PF}_6)_2$ , where L is 1,4,7-trimethyl-1,4,7-triazacyclononane, catalyses the oxygenation of alkanes by peroxyacetic acid or by  $\text{H}_2\text{O}_2$  in the presence of acetic acid to give alkanols, alkanones and alkyl hydroperoxides. The reactions can give large turnovers (up to 1350 after 1 h at 20 °C) and can occur with a high degree of retention of stereochemistry at tertiary carbon atoms. © 1998 Elsevier Science Ltd. All rights reserved.

*Keywords:* Alkanes; Catalysis; Manganese and compounds; Oxygenations

The catalytic oxidation of unactivated aliphatic C-H bonds has been an active area of research for many years [1,2]. Recent attention has been focused on models for enzymic systems and on metal complexes that use cheap clean oxidants such as  $\text{H}_2\text{O}_2$  or  $\text{O}_2$  to bring about selective oxidation under mild conditions [2,3]. In this respect the recent report by Que and coworkers of stereospecific alkane hydroxylation by  $\text{H}_2\text{O}_2$  catalysed by an iron(II) tri(2-pyridylmethyl)amine complex is of particular relevance [4]. Our interest in oxidations catalysed by manganese complexes of 1,4,7-trimethyl-1,4,7-triazacyclononane (TMACN) has led us to explore their potential in hydrocarbon oxidation [5].

The oxidation chemistry of manganese 1,4,7-triazacyclononane catalysts has developed very rapidly since the recent paper describing the use of the dinuclear manganese(IV) complex **1** as a catalyst for low temperature bleaching with  $\text{H}_2\text{O}_2$  [6]. Subsequent studies have reported using **1** and related manganese complexes to catalyse the oxidation of alkenes, alcohols and phenols in both aqueous and organic solution [5,7-13]. We report here that **1** acts as an effective catalyst for alkane oxidation using either peroxyacetic acid or, more interestingly,  $\text{H}_2\text{O}_2$  in the presence of acetic acid.

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**Table 1**Oxidation of hydrocarbons by peroxyacetic acid in CH<sub>3</sub>CN catalysed by complex **1**<sup>a</sup>

| Substrates                            | Total TON <sup>b</sup> | Products  | Yield/mmol dm <sup>-3c</sup> |
|---------------------------------------|------------------------|---|------------------------------|
| cyclohexane                           | 485                    | cyclohexanone<br>cyclohexanol   | 76.6<br>20.6                 |
| cyclohexane <sup>d</sup>              | 700                    | bromocyclohexane<br>cyclohexanone   | 139.0<br>1.0                 |
| hexane                                | 86                     | hexanones <sup>e</sup><br>hexanols <sup>e</sup>   | 11.6<br>5.6                  |
| methylcyclohexane                     | 595                    | 2-, 3- and 4-methylcyclohexanone <sup>f</sup><br>1-methylcyclohexanol<br>2-, 3- and 4-methylcyclohexanol  | 59.0<br>44.0<br>14.0         |
| <i>cis</i> -1,2-dimethylcyclohexane   | 470                    | <i>cis</i> -2,3- and 3,4-dimethylcyclohexanone<br><i>cis</i> -2,3- and 3,4-dimethylcyclohexanol<br><i>cis</i> -1,2-dimethylcyclohexanol<br><i>trans</i> -1,2-dimethylcyclohexanol     | 15.0<br>8.6<br>66.9<br>3.3   |
| <i>trans</i> -1,2-dimethylcyclohexane | 168                    | <i>trans</i> -2,3- and 3,4-dimethylcyclohexanone<br><i>trans</i> -2,3- and 3,4-dimethylcyclohexanol<br><i>trans</i> -1,2-dimethylcyclohexanol<br><i>cis</i> -1,2-dimethylcyclohexanol | 15.9<br>6.7<br>10.0<br>0.9   |
| adamantane <sup>g</sup>               | 306                    | adamantanone<br>adamantanols <sup>h</sup>   | 0.07<br>61.2                 |
| cyclohexanol                          | 1050                   | cyclohexanone   | 210.0                        |

<sup>a</sup> Substrate, 0.4 mol dm<sup>-3</sup>; peroxyacetic acid, 0.5 mol dm<sup>-3</sup>; complex **1**, 0.2 mmol dm<sup>-3</sup>; MeCN reaction volume 5 cm<sup>3</sup>; 30°C; 1h; air. <sup>b</sup>Mols of all products per mol of the catalyst. <sup>c</sup>Product yields following treatment with PPh<sub>3</sub>. <sup>d</sup>In the presence of BrCCl<sub>3</sub>, 2.0 mol dm<sup>-3</sup>. <sup>e</sup>2- : 3-one = 71 : 29; 2- : 3-ol = 55 : 45. <sup>f</sup>2- : 3- : 4-one = 25 : 55 : 20. <sup>g</sup>A suspension of the substrate, 2.0 mmol. <sup>h</sup>1- : 2-ol = 95 : 5.

The data (Table 1) show that **1** in acetonitrile is surprisingly effective at catalysing the rapid oxidation of alkanes by peroxyacetic acid. Both ketones and alcohols are obtained and alcohols, as expected [7,10], are oxidised to ketones. 3-Chloroperoxybenzoic acid can also be used but the oxidation yields are lower. In the absence of **1** negligible oxidation occurs in 1 h. GC analysis of the reaction mixtures, before and after treatment with PPh<sub>3</sub> [14], shows that alkyl hydroperoxides are formed in the initial stages of the oxidations and these are subsequently converted into alcohols and ketones. Examination of the regioselectivity of the oxidations reveals a small preference for reaction at C(2) over C(3) with hexane, and for C(3) and C(4) over C(2) with methylcyclohexane. The relative reactivity of the tertiary to secondary C-Hs in the methylcyclohexanes increases from 2 to 6 to 12 for the *trans*-1,2-dimethyl-, methyl- and *cis*-dimethyl-compounds respectively. The

oxygenations of *cis*- and *trans*-1,2-dimethylcyclohexane afford tertiary alcohols with a marked preference for retention of stereochemistry ( $RC_{cis}$  and  $RC_{trans}$  of 91 and 83%, respectively<sup>1</sup>).

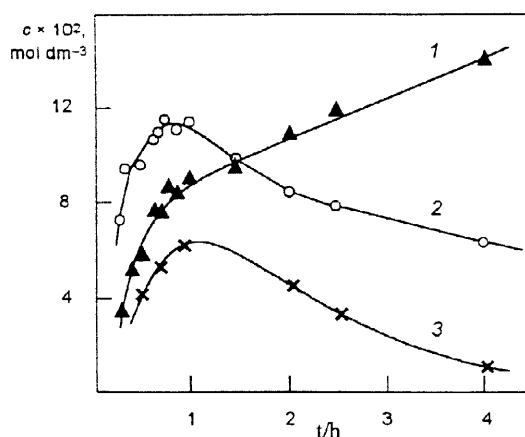
Complex **1** also catalyses alkane oxygenations by *t*-BuOOH, PhIO and H<sub>2</sub>O<sub>2</sub> in MeCN, although these reactions are much less efficient and occur without retention of configuration. Most interestingly, the oxidations by H<sub>2</sub>O<sub>2</sub> in MeCN are accelerated dramatically by the presence of a carboxylic acid. Table 2 shows selected data for reactions in the presence of acetic acid. When the acetic acid is replaced by formic, propionic or trifluoroacetic acid or acetic anhydride the total turnover numbers (TON) for hexane oxidation are 0, 770, 345 and 400, respectively. The absence of hexane oxidation products from reactions in formic acid we believe arises from the latter acting as a reducing agent and competing effectively with hexane by trapping all the active oxidant. The alkane oxidations by the H<sub>2</sub>O<sub>2</sub>/HOAc/**1** system can also be carried out in acetone and less efficiently in methanol, however, no oxygenated products are obtained from reactions in pure acetic acid.

**Table 2**

Oxidation of alkanes by H<sub>2</sub>O<sub>2</sub> and acetic acid in CH<sub>3</sub>CN catalysed by complex **1**<sup>a</sup>

| Substrate                | Total TON <sup>b</sup> | Products  | Yields/mmol dm <sup>-3</sup> c |
|--------------------------|------------------------|---|--------------------------------|
| hexane                   | 1350 <sup>d</sup>      | hexanones <sup>e</sup><br>hexanols <sup>e</sup> | 155<br>115                     |
| cyclohexane              | 640                    | cyclohexanone<br>cyclohexanol                   | 51<br>71                       |
| cyclohexane <sup>f</sup> | 13                     | bromocyclohexane<br>cyclohexanone               | 2.6<br>---                     |
| cycloheptane             | 850                    | cycloheptanone<br>cycloheptanol                 | 70<br>100                      |

<sup>a</sup> Substrate, 0.4 mol dm<sup>-3</sup>; acetic acid, 1.0 mol dm<sup>-3</sup>; H<sub>2</sub>O<sub>2</sub>, 0.5 mol dm<sup>-3</sup>; complex **1**, 0.2 mmol dm<sup>-3</sup>; alkane, 0.4 mol dm<sup>-3</sup>; MeCN to give total volume 5 cm<sup>3</sup>; 20 °C; 1 h. <sup>b</sup> Mols of products per mol of catalyst. <sup>c</sup> Product yields following treatment with PPh<sub>3</sub>. <sup>d</sup> H<sub>2</sub>O<sub>2</sub>, 1.0 mol dm<sup>-3</sup>. <sup>e</sup> 2- : 3-one = 57 : 43 and 2- : 3-ol = 77 : 23. <sup>f</sup> In the presence of BrCCl<sub>3</sub>, 0.1 mol dm<sup>-3</sup>, 10 min.



**Fig 1** Oxidation of hexane (0.4 mol dm<sup>-3</sup>) by H<sub>2</sub>O<sub>2</sub> (0.5 mol dm<sup>-3</sup>) in MeCN at 20 °C in the presence of CH<sub>3</sub>COOH (1.0 mol dm<sup>-3</sup>) catalysed by **1** (0.2 mmol dm<sup>-3</sup>). Curves 1 and 2, hexanones and hexanols, respectively, measured after treatment with PPh<sub>3</sub>. Curve 3, hexyl hydroperoxides obtained by comparison of chromatograms before and after treatment with PPh<sub>3</sub>.

The time dependence of hexane oxidation (Fig. 1) shows that the reaction is biphasic; the first

<sup>1</sup> Parameter  $RC_{cis} = 100(c_{cis} - c_{trans}) / (c_{cis} + c_{trans})\%$ ; parameter  $RC_{trans} = 100(c_{trans} - c_{cis}) / (c_{trans} + c_{cis})\%$ , where  $c_{cis}$  and  $c_{trans}$  are concentrations of *cis*- and *trans*-1,2-dimethylcyclohexanol, respectively

rapid phase, involving alkyl hydroperoxide formation, is complete in 1 h and is followed by a slow transformation of hydroperoxide into ketone. The oxidations of *cis*- and *trans*-1,2-dimethylcyclohexane give both tertiary hydroperoxides and alcohols with the measured stereoselectivity being greater before ( $RC_{trans} = 90\%$ ) than after ( $RC_{cis} = 54\%$  and  $RC_{trans} = 66\%$ ) treatment with  $PPh_3$ .

Both the catalytic systems, with  $CH_3CO_3H$  and with  $H_2O_2/HOAc$ , have the characteristics of radical processes (some loss of stereochemistry, the formation of hydroperoxides and the formation of bromoalkanes from oxidations in the presence of the radical scavenger  $BrCCl_3$ ). This conclusion is further supported by competitive oxidations of cyclopentane, cyclooctane and cyclododecane with cyclohexane which show that the relative reactivities of the substrates are similar although not identical to those obtained using  $O_2/H_2O_2/h\nu$ , a system which is known to produce  $HO\cdot$  radicals [15]. By analogy with Mn(III) porphyrin-catalysed alkane oxidations, the reactions catalysed by **1** can be rationalised by assuming the active oxidant is a manganese complex, possibly an  $O=Mn(V)$  species as suggested very recently by Barton *et al.* [13], which reacts by hydrogen atom abstraction in a solvent cage or via an 'oxygen-rebound' mechanism [16]: both these routes would afford products with retention of stereochemistry. Alkyl radicals,  $R\cdot$ , that escape from the solvent cage react with dioxygen to generate  $ROO\cdot$ , and subsequently  $ROOH$  with loss of stereochemistry. This accounts for the much greater stereoselectivity of the oxidation of 1,2-dimethylcyclohexanes by the  $H_2O_2/HOAc/1$  system prior to  $PPh_3$  reduction. Since under the GC conditions the tertiary hydroperoxides are thermolysed to alkoxy radicals that undergo fragmentation to ring-opened products and the only alcohol detected is that formed within the solvent cage or by oxygen-rebound.

Work is in progress to obtain definitive mechanistic information and to optimise these systems.

**Acknowledgements:** G. B. S. thanks the University of York for giving him the opportunity to carry out this work and the Royal Society for supporting a stay in York (Ex-Quota visit fSU).

#### References

- [1] Sheldon RA, Kochi JK. Metal-catalysed oxidations of organic compounds. New York: Academic Press, 1981.
- [2] Shilov AE, Shul'pin GB. Chem. Rev. 1997;97:2879-2932.
- [3] Sheldon RA. J.Chem. Technol. Biotechnol. 1997;68:381-388.
- [4] Kim C, Chen K, Kim J, Que L. J. Am. Chem. Soc. 1997;119:5964-5965.
- [5] Gilbert BC, Kamp NWJ, Lindsay Smith JR, Oaks J. J. Chem. Soc., Perkin Trans. 2, 1997:2161-2165.
- [6] Hage R, Iburg JE, Kerschner J, Koek JH, Lempers ELM, Martens RJ, Racherla US, Russell SW, Swarthoff T, van Vliet MRP, Warnaar JB, van der Wolf L, Krijnen B. Nature (London), 1994;369:637-639.
- [7] De Vos D, Bein T. Chem. Commun. 1996:917-918.
- [8] Quee-Smith VC, DelPizzo L, Jureller SH, Kerschner JL, Hage R, Inorg. Chem. 1996;35:6461-6465.
- [9] Hage R. Recl. Trav. Chim. Pays-Bas, 1996;115:385-395.
- [10] De Vos DE, Bein T. J. Organomet. Chem. 1996;520:195-200.
- [11] Zondervan C, Hage R, Feringa BL. Chem. Commun. 1997:419-420.
- [12] Bolm C, Kadereit D, Valacchi M. Synlett. 1997:687-688.
- [13] Barton DHR, Choi S-H, Hu B, Smith JA. Tetrahedron, 1998;54:3367-3378.
- [14] Shul'pin GB, Nizova GV, Kozlov YuN. New J.Chem. 1996;20:1243-1256.
- [15] Baxendale JH, Wilson JA. Trans. Faraday Soc. 1957; 53:344-356.
- [16] Meunier B. Chem. Rev. 1992;92:1411-1456.