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Oxidation of Alkanes Catalyzed by Binuclear Metal Complexes: Control by the Coordination Sphere

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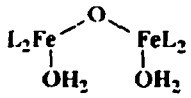
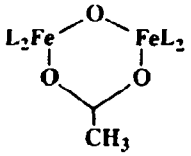
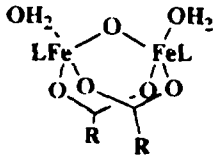
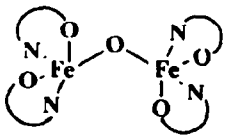
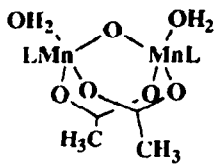
Abstract : The oxidation of cyclohexane by t-butyl hydroperoxide is catalyzed by binuclear oxo-bridged non heme iron complexes. The effects of varying the coordination sphere of iron on catalytic activity are studied pointing to the overall charge of the complex being a key factor. An active dimanganese complex is found to be much more robust than the corresponding iron complex.

Binuclear oxo- or hydroxo-bridged non-heme ferric centers, have been identified in methane monooxygenase and ribonucleotide reductase, where they catalyze a variety of oxidation reactions.[1] Both systems can utilize peroxides for enzymatic activity, suggesting that Fe-OOH(R) or Fe=O complexes are reactive intermediates.[2] The ability of model complexes of this category of iron center to catalyze the oxidation of saturated hydrocarbons has been only recently recognized.[3] The most active catalysts contained two bipyridine ligands per iron and an exchangeable coordination site, required for the binding of the oxidant to the iron center and its activation.[4] However, such an environment greatly differs from that of the natural diiron sites, where iron coordination sphere is dominated by oxygen atoms.[5] We thus found crucial to explore the catalytic properties of the model complexes with respect to changes in the coordination environment of the metal ions. In this report, we compare eight different μ-oxo bridged diferric complexes, with either N_4O_2 or N_2O_4 environments, and one manganese analog in terms of their ability to catalyze cyclohexane oxidation by tert-butyl hydroperoxide (TBHP, Table 1).[6] All ferric complexes have been prepared by allowing the correct equivalent number of bidentate nitrogen ligand to react with ferric perchlorate in MeOH or CH_3CN, in the presence of a carboxylate salt when needed (self-assembly method). ^1H NMR, UV-visible and Raman resonance spectroscopies as well as elemental analysis were in full agreement with the proposed structures (Table 1)[7,8]. Some of the complexes had been previously characterized.[6,9] Mn complex was prepared according to reference 9b. No mixed-valence impurities could be detected by EPR spectroscopy.

At ambient temperature and pressure under an argon atmosphere, 3.5 μmoles catalyst reacted with 0.49 mmoles TBHP and 3.85 mmoles cyclohexane in 4.5 ml acetonitrile. At time intervals, the reaction mixture was analyzed by GC, in the presence of an internal standard. Cyclohexanol and cyclohexanone were the major reaction products with a ketone to alcohol ratio of about 1:1, which was not significantly dependent on the nature of the iron ligands (data not shown). Also, minor amounts of tert-butyl cyclohexyl peroxide were detected (about 10% of total product). No oxidation of cyclohexane took place in the absence of the catalyst. Running the reaction under dynamic argon atmosphere did not affect the product yields, suggesting that O_2,

Table 1. Oxidation of Cyclohexane by TBHP Catalysed by μ-oxo Dinuclear Fe- or Mn Complexes.

N/O	catalysts		ligands	% yield[a] (reaction time)	V_0[b] 1rst run	2nd run
		1	bipy	42 (7 min)	17	2
N_4O_2		2	bipy	38 (2 h)	2	0.4
		3	Me-bipy	53 (10 min)	8	0.6
		4	PyIm	42 (24 h)	0.1	0.01
N_2O_4[c]		5	bipy	37 (10 h)	0.15	0.02
		6	CO_2Mebipy	40 (24 h)	0.10	0.01
		7	bipy	35 (20 h)	0.10	0.01
		8	HQ	0	0	0
N_2O_4		9	bipy	40 (30 min)	2	2

[a] Yields of cyclohexanol + cyclohexanone based on starting TBHP. The reaction time is the time needed to consume all the peroxide. *It is expressed in hours (h) or minutes (min).* [b] V_0 *(first run) is the initial oxidation rate and is expressed in mol product/mol* catalyst/min. At the reaction time indicated in the table, a second aliquot of TBHP is added and V_0 (second run) is determined. [c] The carboxylate bridges are acetates in 5 and 6, and MPDP in 7.

derived from dismutation of TBHP, was not involved in the formation of the products observed.[4]

Table 1 indicates, for all tested catalysts, the total alcohol + ketone yields, reaction time, initial turnover number per minute after addition of the first aliquot of TBHP and also after a second addition of TBHP (at the end of the reaction). The difference between the two V_0 values is indicative of the inactivation of the catalyst during multiple turnovers.

From Table 1, one can make the following observations. First, the bipyridine ligand provides by far the most active catalyst. Complex **1** yields 42 % oxidation products, based on the limiting TBHP, in a few minutes, with the highest turnover number per minute reported so far for a non heme iron catalyst. Complex **2** is less active showing that the bidentate acetate bridge is less easily dissociable from the iron center than aquo ligands to generate an open site. The presence of a para methyl group on the bipyridine ligand improved the activity of such a (μ-oxo)(μ-acetato) diferric center (compare **2** and **3**). On the other hand an ester substituent had a negative effect (compare **5** and **6**). Moreover, pyridine was a better ligand than imidazole (compare **2** and **4**). No correlation between the basicity of the neutral nitrogen ligand and the catalytic activity can be raised up. The N:O ratio of the iron environment has a great effect on the efficiency of the catalysts. The (μ-oxo) bis (μ-carboxylato) diferric complexes **5** and **7**, in which N:O = 2:4, were much less reactive than **1** and **2**, with initial turnover numbers per minute about two orders of magnitude lower and consequently with much longer reaction times. It should be noted that an increased steric hindrance at the carboxylate bridges had a significant effect on the catalytic activity (compare **7** with its bulky dicarboxylate ligand[10] to **5** with acetate bridges). A N:O = 2:4 environment was also achieved in complex **8** in which the bipyridine was replaced by the bidentate hydroxyquinoline ligand. Complex **8** was found to be totally inactive. The strong effects of negatively-charged oxygen ligands might be rationnalized in terms of decreased acidity of the iron center and electrostatic repulsions which make TBHP more difficult to bind. Third, all iron complexes were rapidly inactivated during the reaction and lost approximately 90% of their activity after one run, as shown from the slower cyclohexane oxidation following a second addition of TBHP. Fourth, the dinuclear manganese complex exhibited a remarkable stability and was able to sustain very high turnover numbers. Moreover, it had a rather good catalytic efficiency (2 mol/ mol catalyst/min) much higher than the corresponding iron analog **5**.

In summary, it is still unclear why natural systems have selected carboxylate ligands rather than histidines to make active diferric centers. Whether it is related to their specific function during reductive oxygen activation, a reaction not investigated here, remains to be established with appropriate model complexes. However this study shows that for hydroperoxide-dependent alkane oxidations, the overall charge of the catalyst is a key factor and consequently, neutral nitrogen ligand should be preferred to carboxylato ligands. On the other hand, the potential of non heme dimanganese complexes as catalysts for alkane oxidation should be more extensively explored.[11] It is now under investigation in our laboratory.

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6. *Abbreviations used*: bipy= 2,2'-Dipyridyl; Me-bipy= 4,4'-Dimethyl-2,2'-dipyridyl; PyIm= 2-(2'-Pyridyl)imidazole; CO_2Mebipy= 4,4'-Dimethoxycarbonyl-2,2'-dipyridyl; HQ= 8-hydroxyquinoline; MPDP= m-phenylenedipropionate dianion.

7. Spectroscopic characteristics of μ-oxo bridged diferric complexes are discussed in : Que, L. Jr.; True, A. E. *Prog. Inorg. Chem.* **1990**, *38*, 97-200.

8. *Selected analytical and spectroscopic data* for complexes **4**, **5**, **6**, **7**. For **4** Anal. Calcd for $Fe_2O(C_8N_3H_7)_4(CH_3CO_2)(ClO_4)_3.2H_2O$ ($C_{34}H_{35}Cl_3Fe_2N_{12}O_{17}$): C, 36.99; H, 2.99; N, 15.23; Cl, 9.63; Fe, 10.01. Found: C, 36.90; H, 3.00; N, 15.20; Cl, 9.61; Fe, 9.65. For **5** Anal. Calcd for $Fe_2O(C_{10}H_8N_2)_2(CH_3CO_2)_2(H_2O)_2(ClO_4)(PF_6)$ ($C_{24}H_{26}ClFe_2N_4O_{11}PF_6$): C, 34.35; H, 3.10; N, 6.67; Cl, 4.22; Fe, 13.31; P, 3.69. Found: C, 34.10; H, 3.20; N, 6.70; Cl, 4.70; Fe, 13.07; P, 3.79. For **6** Anal. Calcd for $Fe_2O(C_{14}N_2H_{12}O_4)_2(CH_3CO_2)_2(H_2O)_2(ClO_4)_2$ ($C_{32}H_{34}Cl_2Fe_2N_4O_{23}$): C, 37.5; H, 3.31; N, 5.46; Cl, 6.91; Fe, 10.89. Found: C,37.28; H, 3.51; N, 5.53; Cl, 7,20; Fe, 10.12. For **7** Anal. Calcd for $Fe_2O(C_{10}H_8N_2)_2(C_{12}O_4H_{12})(ClO_4)_2.5H_2O$ ($C_{32}H_{38}Cl_2Fe_2N_4O_{18}$): C, 39.76; H, 3.92; N, 5.83; Cl, 8.34; Fe, 11.61. Found: C, 40.50; H, 4.00; N, 5.90; Cl, 7.47; Fe, 11.77.
Electronic spectrum (in CH_3CN): λ_{max}, nm (ε, $M^{-1}.cm^{-1}$). For **4**: 354 (9360,sh.), 611 (171). For **5**: 454 (773), 485 (681), 693 (101). For **6**: 315 (19270), 461 (993), 493 (908), 699 (159). For **7**: 335 (7452,sh), 464 (792), 493 (774), 699 (129).
^1H NMR (200 MHz, CD_3CN): For all these complexes, the ^1H NMR displays characteristics resonances between 0 and 30 ppm.

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