Importance of Mn–Mn Separation and their Relative Arrangement on the Development of High Catalase Activity in Manganese Porphyrin Dimer Catalysts

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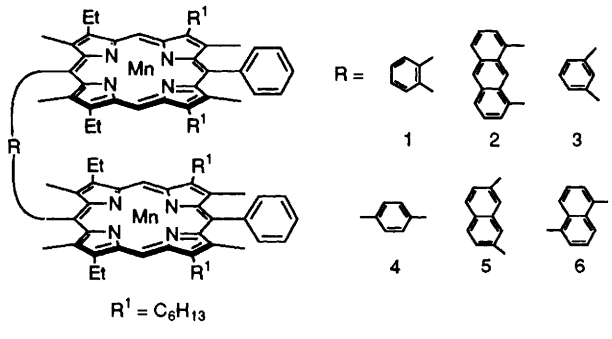
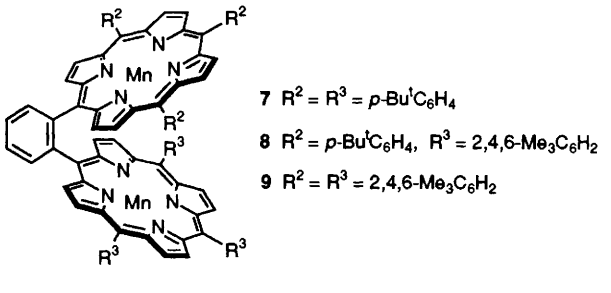
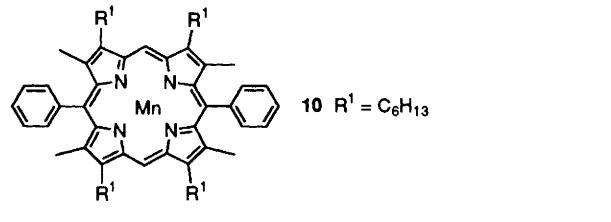
Catalase activity of manganese porphyrin dimers linked by various spacer molecules reveals a remarkable relationship between Mn–Mn separation and arrangement; the highest turnover rate is observed when the two Mn ions can cooperatively interact with a H_2O_2 molecule in the catalyst cavity.

Polynuclear manganese complexes are essential for H_2O_2 disproportionation catalysed by manganese catalases (Mn-CATs), in thermophilic bacteria[1,2] and a lactobacillus.[3] X-Ray structure analysis of *Thermus thermophilus* revealed the two manganese ions are separated by just 3.6 Å.[4] Similar catalase activity was observed at the S_2 state of the photosynthetic water oxidation enzyme,[4] which has a tetranuclear manganese core (2.7 and 3.3 Å separation).[5] Metal–metal separation and relative arrangement are essential in designing an O_2-evolving model complex.[6] Some binuclear manganese complexes have been synthesized and compared with the enzymes.[7] We have reported the modelling reaction of Mn-CAT with manganese porphyrin dimers **2** and **3** in the presence of an appropriate nitrogen base and proposed a Mn^{III}_2/Mn^{IV}_2 redox cycle.[8,9] The Mn–Mn separation and relative arrangement are tunable using different linkers between the two porphyrins. Here, we show the relationship between catalase activity and the Mn–Mn separation as well as their relative positions.

We synthesized various manganese porphyrin dimers **1–9**† and compared their catalase activity with **10**. The O_2 evolution rate was measured in a thermostatted reaction cell equipped with a Clark-type oxygen electrode; turnover number was estimated from initial O_2 evolution rate. Dimers **1** and **2** have close manganese ions (**1**, 3.7;‡ **2**, 4.4 Å‡) and showed high catalase activities, see Fig. 1(*a*). The catalytic activities of **4–6** were negligible. By incorporating bulky mesityl groups at







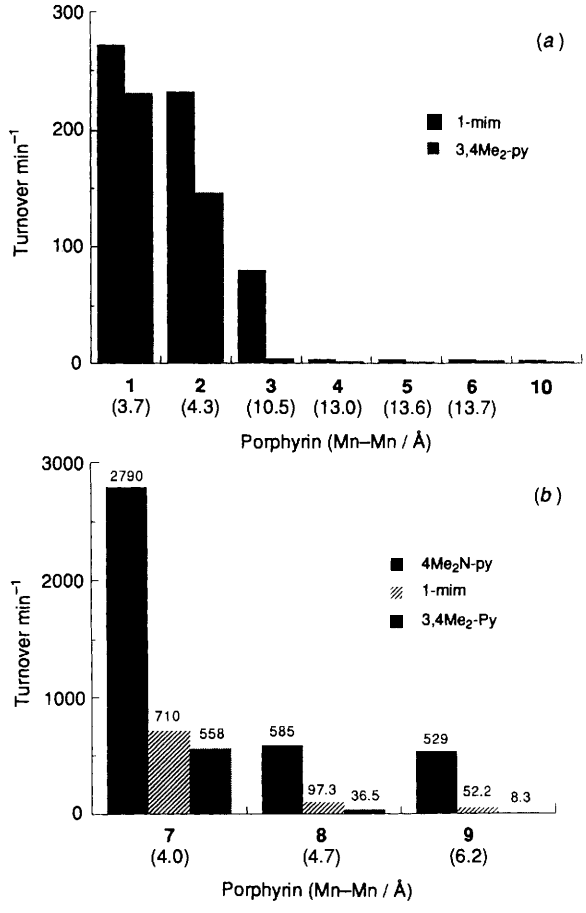


Fig. 1 Catalytic O_2 evolution rate of (*a*) the manganese porphyrin dimers **1–6** and the corresponding monomer **10**, and (*b*) tetraphenylporphyrin-type dimers **7–9** in the presence of different nitrogen bases. Conditions: solvent, acetonitrile–benzonitrile (1 : 0.03–0.07 v/v); T = 10.0 ± 0.2 °C; [Mn dimer] = 1.25 × 10^{-4} mol dm^{-3}; [base] = 0.125 mol dm^{-3}; [H_2O_2] = 6.4 × 10^{-2} mol dm^{-3}. The metal–metal separations of the porphyrin dimers were optimized by means of MM+.§

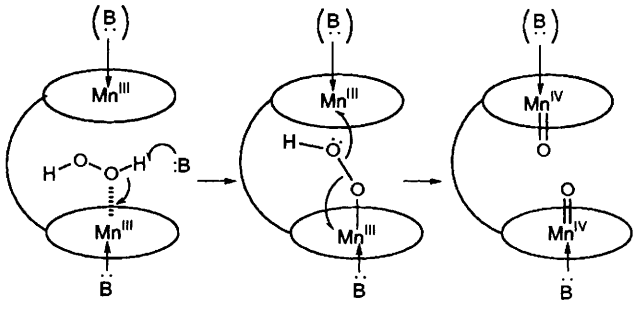


Fig. 2 Proximal effect of manganese ions and the role of base in the decomposition of hydrogen peroxide

meso positions, the metal separation can be changed from 3.9 to 6.2 Å.‡ As expected from the above results, the catalytic activity drastically decreased, Fig. 1(*b*). Thus when the Mn–Mn separation is *ca.* 4 Å, the dimer showed highest catalase activity. This indicates that the two manganese ions cooperatively function in the rate-determining step of the disproportionation of H_2O_2. From our mechanistic study including kinetic and isotope-scrambling experiments,[8] the rate-determining step of the catalase reaction with the catalyst **2** is the formation of the Mn^{IV}_2 complex from the initial Mn^{III}_2 dimer. High catalase activity in our modelling system develops, therefore, when each oxygen atom of a H_2O_2 molecule interacts with each Mn ion of the dimer (Fig. 2). The homolytic cleavage of the O–O bond could be facilitated by the coordination of each oxygen atom in the peroxy ion to the manganese ions with formation of the Mn^{IV}_2 complex. This distance is in good accord with the Mn–Mn separation in the hypothetical Mn–O–O–Mn complex, irrespective of its conformation to be either a Z-shaped bent (4.0–4.5 Å) or an *endo* form (3.8–4.0 Å).§

The reaction of hydrogen peroxide with manganese porphyrins requires an appropriate nitrogen base. The demonstrated catalytic oxygen evolution also showed remarkable base dependency. We investigated three nitrogen bases, 4-dimethylaminopyridine (4-Me_2N-py, $pK_a = 9.47$), 1-methylimidazole (1-mim, 7.33) and 3,4-dimethylpyridine (3,4-Me_2N-Py, 6.46). Observed catalytic activity correllated well with basicity; the base assists in deprotonation of hydrogen peroxide and donates electrons to the metal enhancing the cleavage of the O–O bond of the coordinated hydroperoxide group. Usually, manganese porphyrins bearing no sterically hindered group(s) yield the corresponding stable six-coordinated complex.

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Footnotes

† *Selected spectroscopic data*: **3**: FAB MS *m/z* = 1289 (M^+); UV–VIS (CH_2Cl_2) λ_{max} 579, 482, 361 nm. **4**: FAB MS *m/z* = 1513 (M^+); UV–VIS (CH_2Cl_2) λ_{max} 546, 485, 384 nm. **5**: FAB MS *m/z* = 1564 (M^+); UV–VIS (CH_2Cl_2) λ_{max} 683, 571, 480, 369 nm. **6**: FAB MS *m/z* = 1564 (M^+); UV–VIS (CH_2Cl_2) λ_{max} 562, 481, 385 nm.

‡ Metal–metal distances of the porphyrin dimers were estimated from the values of the corresponding free-base porphyrins by means of computer-generated modelling, which was performed using the MM+ package inside HYPERCHEM. The calculated separations of **1** (3.7 Å) and **2** (4.3 Å) were fair accordance with the observed values in the copper (3.90 Å)[10] and nickel complexes (4.56 Å)[11] of similar porphyrins.

§ The Mn–Mn separation was estimated by assuming Mn–O 1.80, O–O 1.45 Å, and Mn–O–O 135°.

¶ Estimated from the reported Michaelis–Menten constants of *L. plantarum*;[4] K_m = 250 mmol dm^{-3} and $V_{max} = 3.1 \times 10^5$ dm^3 mol^{-1} s^{-1}.[3]

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