DALTON COMMUNICATION

Tuning the metal-based redox potentials of manganese *cis*,*cis*-1,3,5-triaminocyclohexane complexes

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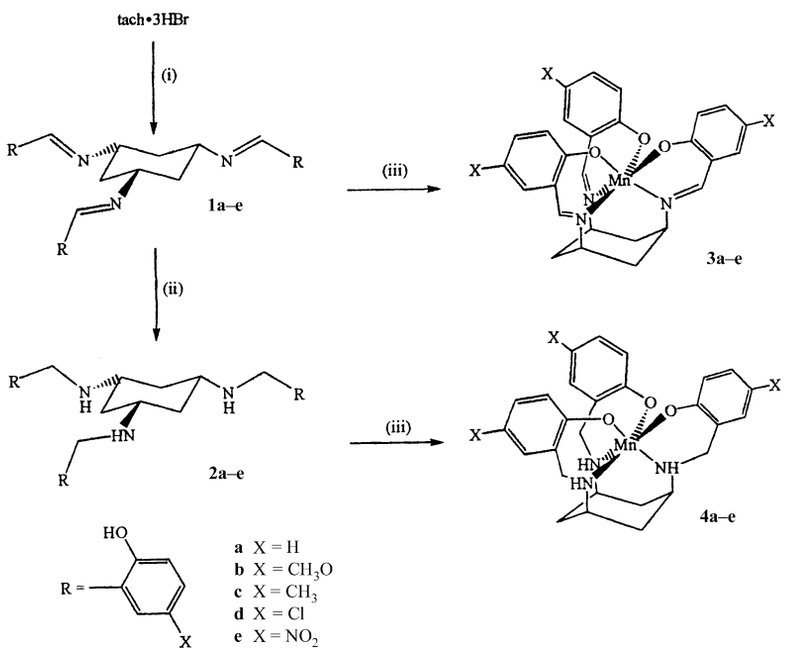
A selection of 5-substituted salicylaldehydes have been reacted with *cis*,*cis*-triaminocyclohexane to prepare a series of tri-imine and tri-amine ligands; cyclic voltammetry has been used to show that the electronic effect of the substituent has a marked and systematic effect on the Mn^{III}/Mn^{IV} and Mn^{III}/Mn^{II} redox potentials of their manganese complexes.

Much of the recent interest in Mn coordination chemistry stems from the identification of manganese in metalloenzymes such as the oxygen evolving centre (OEC) of photosystem II,[1] catalases,[2] and superoxide dismutases.[3] Numerous manganese complexes have been prepared with the aim of modelling these enzymes. In this respect our recent synthesis of N_3 face-capping tri-imine ligands, from the condensation of aldehydes and *cis*,*cis*-1,3,5-triaminocyclohexane (tach), provides a useful approach to a wide range of biomimetic metal complexes.[4] A further important target, which would aid the design of more effective functional models of manganese containing active sites,[5,6] is the ability to control the metal-based redox potentials of the complexes. This is the subject of the work described below.

We have used salicylaldehyde and four of its commercially available 5-substituted derivatives to prepare the symmetrical tri-imines (**1a**–**e**) and by reduction with sodium borohydride the analogous tri-amine ligands (**2a**–**e**) (Scheme 1).† The substituents were selected to encompass a wide range of electronic effects from electron-donating methoxy- (σ_p −0.28) to strongly electron-withdrawing nitro- (σ_p +0.81).[7] Each of the ligands was reacted with equimolar amounts of manganese(III) acetate dihydrate in methanol, in the presence of excess base, under an inert atmosphere to give the mononuclear manganese(III) complexes (**3a**–**e** and **4a**–**e**).‡[8] Ligands **1a** and **2a** were also reacted with gallium(III) nitrate under the same conditions to give the gallium complexes **5** and **6**, respectively.[8a]

The cyclic voltammograms (CV) of the complexes (**3a**–**e**, **4a**–**e**) in DMF exhibit a quasi-reversible one-electron Mn^{III}/Mn^{IV} oxidation and a less reversible Mn^{III}/Mn^{II} reduction process over the potential range −1.5 to 0.5 V *vs.* Fc^+/Fc.§ To confirm that the redox processes are metal- and not ligand-centred, we carried out two experiments. In the first, we used cyclic voltammetry to show that the gallium tri-imine and tri-amine complexes, **5** and **6,** do not undergo any redox processes between −1.5 and 0.5 V, as would be expected of a redox inactive metal. A poorly reversible process was observed at ≈0.7 V (also seen with some of the manganese complexes) which we attribute to oxidation of the ligand. In the second experiment, we oxidised the manganese(III) complex **3a** with $[FeCp_2]PF_6$ in methanol, under an inert atmosphere, to give the corresponding manganese(IV) species **7** which was obtained as intensely blue-coloured crystals.¶ Comparison of the structures



Scheme 1 *Reagents and conditions*: (i) Et_2O–H_2O, 3 equiv. NaOH and appropriate salicylaldehyde, rt, 2 h, >90%; (ii) **1a**–**e**, CH_3OH, 10 equiv. $NaBH_4$, reflux 4 h, 50–70%; (iii) **1a**–**e**, **2**–**e**, dry CH_3OH, N_2, Mn(III) acetate·$2H_2O$, Et_3N, rt overnight, chromatography (neutral aluminium oxide, 85 : 15 v/v, CH_2Cl_2–CH_3OH) 60–80%.

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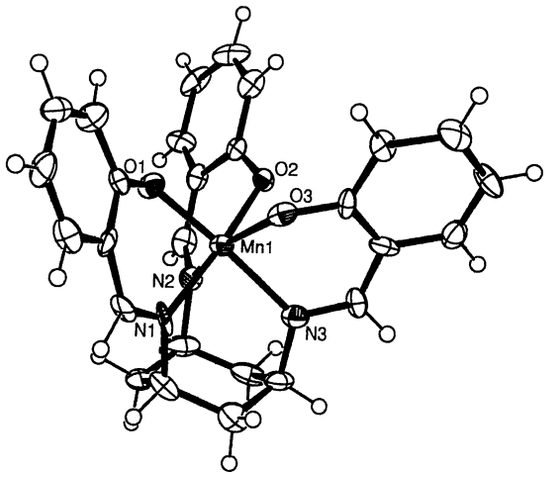

Fig. 1 ORTEP[9] representation (50% probability ellipsoids) of manganese complex **3a**, selected bond distances (Å): Mn–O(1) 1.906(8), Mn–O(2) 1.906(7), Mn–O(3) 2.112(8), Mn–N(1) 2.016(9), Mn–N(2) 2.234(11), Mn–N(3) 2.124(10). For comparison the equivalent data for **7** are (Å): Mn–O(1) 1.875(6), Mn–O(2) 1.861(7), Mn–O(3) 1.857(6), Mn–N(1) 2.011(8), Mn–N(2) 2.005(7), Mn–N(3) 2.007(7).

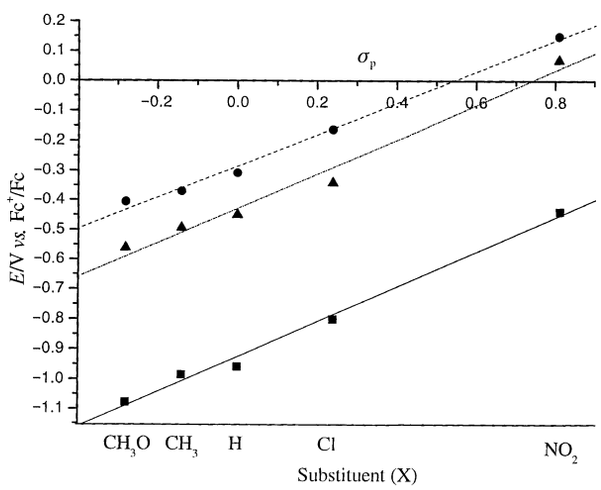

Fig. 2 Hammet plot of redox potentials (*vs.* Fc^+/Fc, in DMF at 298 K with 0.2 M $[Bu_4N]BF_4$) against substituent parameter, σ_p; Mn^{III}/Mn^{IV}: ● complexes **3a**–**e** and ▲ complexes **4a**–**e**; Mn^{III}/Mn^{II}: ■ complexes **3a**–**e**.

(from single crystal X-ray diffraction) of **3a** and **7** shows that the Mn–O(3) and Mn–N(2) bonds of the former are significantly elongated, whereas all the Mn–O and all the Mn–N bond lengths of the latter are very similar (Fig. 1).‖ These observations are consistent with a substantial tetragonal Jahn–Teller distortion of the high-spin d^4 manganese(III) complex and the absence of such a distortion for the d^3 manganese(IV) species.[12] This is further supported by the magnetic susceptibilities of **3a** and **7**, using the Evans method,[13] [295 K, $(CD_3)_2SO$)] as 5.0 and 4.0 μ_B respectively. When **7** was subjected to cyclic voltammetry, under the conditions used for the tri-imine complexes, its CV was identical to that of **3a**.

The Mn^{III}/Mn^{IV} and Mn^{III}/Mn^{II} redox potentials (*vs.* Fc^+/Fc) of complexes **3a**–**e** and **4a**–**e** are strongly dependent on the electronic properties of the substituent.§ The former for both series of complexes give excellent linear correlations ($r \geq 0.990$) when plotted against the Hammett substituent constant,[7] σ_p, (Fig. 2).** For the Mn^{III}/Mn^{II} redox potential, the equivalent linear correlation is also very good for the tri-imines **3a**–**e** (r 0.996) but it is rather more scattered for the corresponding tri-amine species **4a**–**e** (r 0.808). Interestingly, the reaction constants per substituent, ρ, for the redox processes (determined from the slopes of the appropriate Hammett plots) are large and very comparable (Mn^{III}/Mn^{IV}: **3a**–**e**, $\rho = -2.97 \pm 0.14$; **4a**–**e**, $\rho = 3.26 \pm 0.27$; Mn^{II}/Mn^{III}: **3a**–**e**, $\rho = -3.31 \pm 0.17$) highlighting the significant influence of the substituents on the redox potentials of the two processes. These electronic effects are larger than typically observed for reactions/equilibria of phenols,[14] although Borovik *et al.*[15] have reported a ρ value of 4.55 for the VO^{IV}/VO^{V} couple of some oxovanadium bis-amidophenolate complexes. It seems likely that, as proposed by Borovik *et al.*, the substituent effect in these chelate complexes is being relayed to the metal ion by two pathways, *via* the phenolate and the imine groups, and the Hammett correlation is measuring the combined effects of both. The excellent correlation with σ_p, however, suggests that the dominant substituent effect is *via* the phenolate group.

Controlling the redox potential of manganese in manganese enzymes is crucial to ensure maximum activity in biological systems. For iron and manganese superoxide dismutases, for example, the optimum value (0.2–0.4 V *vs.* NHE)[16] is determined by the amino-acids in the second coordination sphere which tune the proton coupled Fe^{III}/Fe^{II} and Mn^{III}/Mn^{II} redox potentials.[17] The present study shows that with model systems the electronic effects of the substituents on the ligand can be used, in an analogous way, to tune the redox potential of a single manganese couple over a range of ≈0.6 V. Importantly, for the Mn^{III}/Mn^{IV} couple, this spans the redox potential of many manganese enzymes. The complexes described in this communication are currently under investigation as manganese superoxide dismutase and catalase models.

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Notes and references

† Each ligand has been fully characterised by ESMS, NMR, IR and UV-Vis techniques.

‡ Each complex has been fully characterised by ESMS, IR, UV-Vis techniques and C,H,N elemental analyses.

§ Cyclic voltammetry was performed on an EG&G Princeton Applied Research potentiostat/galvanostat model 273 using a standard three electrode configuration with platinum working (0.5 mm diameter disk) and counter electrodes and an Ag/AgCl reference electrode. All experiments were carried out under N_2 at ambient temperature with 0.2 M $[Bu_4N]BF_4$ as the supporting electrolyte. No IR compensation was applied to the recorded CVs. The Fc^+/Fc couple was used to monitor the reference electrode and was observed at 0.49 V.

Electrochemical data for complexes **3a**–**e** and **4a**–**e**. For Mn^{III}/Mn^{IV} processes, values of $E_{1/2}$ were independent of scan speed (0.05–0.5 mV s^{-1}). Also, plots of peak current *vs.* scan speed were linear. Relevant data, $E_{1/2}$ (peak to peak separation, ΔE, and ratio of current of anodic and cathodic waves, i_a/i_c); Fc^+/Fc, 0.49 V (78 mV, 0.98); **3a**, −0.31 V (98 mV, 1.02); **3b**, −0.41 V (120 mV, 0.98); **3c**, −0.37 V (82 mV, 1.02); **3d**, −0.17 V (91 mV, 0.98); **3e**, 0.15 V (88 mV, 1.00); **4a**, −0.49 V (103 mV, 1.10); **4b**, −0.56 V (143 mV, 0.67); **4c**, −0.49 V (154 mV, 1.12); **4d**, −0.34 V (128 mV, 0.93); **4e**, 0.07 V (189 mV, 0.92). For Mn^{III}/Mn^{II} processes, the return oxidation wave was clearly present but much less distinguishable than the return reduction wave in the Mn^{III}/Mn^{IV} processes, $\Delta E > 290$ mV in all cases. Relevant data E for the reduction wave *vs.* Fc^+/Fc: **3a**, −0.96 V; **3b**, −1.08 V; **3c**, −0.99 V; **3d**, −0.80 V; **3e**, −0.44 V.

¶ Typical procedure for the synthesis of **7**. Complex **3a** (0.1 mmol, 5 mg) and $[FeCp_2]PF_6$ (0.1 mmol, 3.6 mg) were combined in a 1 : 1 v/v mixture of dry CH_3OH and CH_2Cl_2 (4 cm^3) and stirred for 2 h. The solvent was removed under vacuum and the residue was redissolved in CH_3OH. Layering with Et_2O afforded **7** as dark blue crystals which were characterised by ESMS, IR and UV-Vis techniques.

‖ Crystal data for **3a**: $C_{28}H_{26}Cl_2N_3O_3Mn$, $M = 578.36$, $a = 10.192(2)$, $b = 15.336(3)$, $c = 16.322(5)$ Å, $V = 2551.3(11)$ $Å^3$, orthorhombic, space group $Pna2_1$ (no. 33), $Z = 4$, μ(Mo-K_α) = 0.764 mm^{-1}, 1379 (all unique), $T = 150$ K. Final $R1$, $wR2$ on all data (1379 reflections) 0.0934, 0.1022. $R1$, $wR2$ on $[I_o > 2\sigma(I_o)]$ (916 reflections) 0.0371, 0.0823.

Crystal data for **7**: $C_{27}H_{24}N_3O_3MnPF_6$, $M = 638.40$, $a = 36.598(13)$, $b = 7.890(1)$, $c = 22.623(7)$ Å, $\beta = 126.725(15)°$, $V = 5235(3)$ $Å^3$, monoclinic, space group $C2/c$ (no. 15), $Z = 8$, μ(Mo-K_α) = 0.645 mm^{-1}, 4859/4508 measured/unique ($R_{int} = 0.117$), $T = 150$ K. Final $R1$, $wR2$ on all data (4508 reflections) 0.2395, 0.2525. $R1$, $wR2$ on $[I_o > 2\sigma(I_o)]$ (1720 reflections) 0.0686, 0.1734.

The structures of **3a** and **7** were solved by direct methods (SIR-92)[10] and refined against F^2 (SHELXL 93)[11]. **3a** was refined with all non-hydrogen atoms anisotropic. **7** was refined with only the manganese atom having anisotropic thermal parameters (a full anisotropic refinement on non-hydrogen atoms gave negative values for thermal parameters on some atoms; this is probably because crystals of **7** were weakly diffracting and only a relatively small amount of data was collected). In both **3a** and **7** the overall structures of the complexes are clear. Hydrogen atoms were placed at calculated positions and refined as riding atoms with isotropic displacement parameters. A dichloromethane solvent molecule in **3a** was disordered with the carbon atom occupying two positions (0.60 and 0.40). CCDC reference numbers 155490 and 155491. See http://www.rsc.org/suppdata/dt/b1/b102103f/ for crystallographic data in CIF or other electronic format.

** To correct the gradient, in mV, to a conventional ρ value requires dividing by 3, to take into account the three substituents per complex and by -59.2 mV $[-2.303(RT/zF)]$.

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