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Towards hydroperoxovanadium complexes: the X-ray crystal structure of a peroxovanadium(v) complex containing a $V(O_2)(RCO_2H)(H_2O)_2$ cluster with hydrogen bond inter-linkages†

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Received (in Cambridge, UK) 30th January 2001, Accepted 22nd March 2001
First published as an Advance Article on the web 3rd May 2001

The molecular structure of the oxo-peroxovanadium complex $[VO(O_2)(bpaH)]ClO_4{\cdot}2H_2O$, containing the new ligand *N,N*-bis(2-pyridylmethyl)-β-alanine (bpaH) reveals tight binding of the carboxylic acid function to the vanadium centre through its doubly bonded oxygen; the carboxylic acid proton mediates hydrogen bonding interactions comprising the peroxo group and the two waters of crystallisation, thus providing the basis for the potential formation of a hydroperoxo species.

Authentic peroxovanadium complexes as well as peroxovanadium complexes generated *in situ* have been employed as catalysts and in stoichiometrically conducted reactions as oxo transfer reagents for alcohols, arenes, alkenes and thioethers.[1,2] Likewise, the bromination of functionalised arenes is carried out by peroxovanadium complexes, or by vanadium compounds in the presence of H_2O_2.[3,4] Peroxovanadium intermediates have also been proposed for the enzymatic conversion of halide to hypohalous acid (or another Hal^+ species) by vanadate-dependent algal and fungal haloperoxidases in the presence of peroxide,[4–7] an assumption which has been fortified by the structural characterisation of the peroxo form of chloroperoxidase from the fungus *Curvularia inaequalis*.[8] Both the *in vitro* and *in vivo* oxidation of halide such as bromide is facilitated by an increase of the electrophilicity at the reaction site, *i.e.* by the intermediate formation of a hydroperoxo complex (Fig. 1, left) in the case of the peroxo ligand representing the reaction site,[4,5,9] a suggestion which finds support in the fact that (i) protons are consumed in these reactions,[9] (ii) alkylperoxo complexes are often more effective than the parent peroxides,[1] (iii) the cationic hydroperoxo–oxovanadium moiety is on a lower energy level (more stable) than the corresponding peroxo–oxovanadium species,[10] and (iv) a hydroperoxo form of the active site vanadium in bromoperoxidase from the marine alga *Ascophyllum nodosum* is quite within the bounds of probability as based on ^{17}O NMR evidence.[10] The asymmetric side-on coordination of RO_2^- has previously been reported for $[VO(O_2)(HO_2)(bipy)]$ (bipy = 2,2′-bipyridyl[12a]), $[VO(H_2O)(tBuO_2)(dipic)]$ (dipic = dipicolinate(2−))[12b] and $[\{VO(O_2)_2\}(\mu\text{-}\eta^1,\eta^2\text{-}O_2)\{VO(O_2)H_2O\}]^{2-}$.[13] Based on kinetic investigations, hydroperoxo intermediates have also been made plausible in oxo transfer reactions to metal-centred thiolates using $[VO(O_2)_2(pic)]^{2-}$,[14] and peroxidative halogenations with $[VO(O_2)(bpg)]$ (bpgH = *N,N*-bis(2-pyridylmethyl)glycine).[5,9] An additional point of considerable interest in the context of peroxovanadium complexes is their ability to inhibit phosphotyrosine phosphatases and thus act as insulin mimetics.[15]

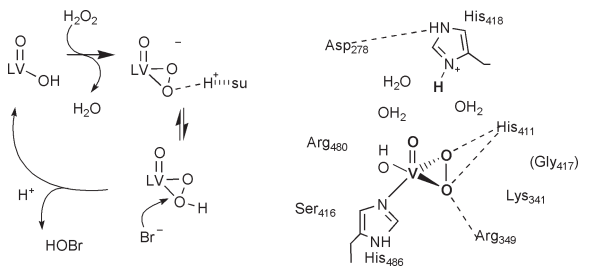
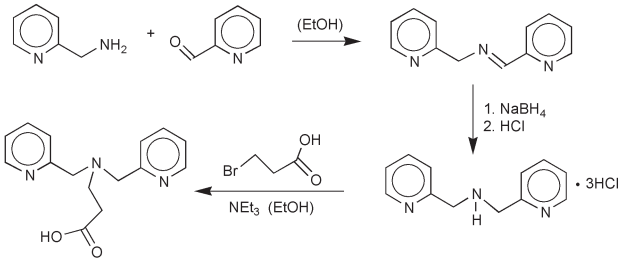


Fig. 1 Left: proposed mechanism for bromide oxidation (su = supporting group). Right: active site of the peroxo form of vanadate-dependent bromoperoxidase from *A. nodosum*, based on the structure of the native *A. nodosum* enzyme[18] and the peroxo form of the *C. inaequalis* peroxidase.[8] Potential mediators for proton transfer are His418, His411 and Asp278.

In the present work we report on a peroxovanadium complex giving rise to a tight hydrogen bonding network in which three different functionalities participate, *viz.* a coordinated and protonated carboxylate, two inter-lattice water molecules and the peroxo ligand. Hence a complex which may represent a preformed hydroperoxo species, or a compound which is able to rapidly and reversibly provide a proton for a hydroperoxo intermediate in catalytic turnover. Our complex thus models a situation which, in the haloperoxidases, is represented by aspartate or the distal histidine plus water molecules at the active site of the enzyme (Fig. 1, right). Aspartate as a mediator for proton-transfer has also been reported for vanadate-incorporated phytase,[16] a semi-synthetic vanadium peroxidase.[17]

The new ligand *N,N*-bis(2-pyridylmethyl)-β-alanine (bpaH) was synthesised† (Scheme 1) by modifying the procedure described for *N,N*-bis(2-pyridylmethyl)-glycine (bpgH).[19] The complex $[VO(O_2)(bpaH)]ClO_4{\cdot}2H_2O$ was obtained† by adding the ligand to an aqueous solution of $K[VO_3]$, followed by treatment with H_2O_2 and finally with dilute $HClO_4$ to adjust the solution to pH 1.7. Orange-coloured crystals were obtained from the ethanolic solution in the cold.

The molecular structure‡ of the compound is shown in Fig. 2; hydrogen bonding interactions have been indicated by dashed lines. The basic structure of the cation $[VO(O_2)(bpaH)]^+$ is a pentagonal bipyramid, with the peroxo ligand (O1 and O2) and the three nitrogens (N1, N2 and N3) of bpaH in the plane, and the oxo group O3 and carboxylic acid oxygen O4 in the apical positions. The ligand bpaH coordinates to the vanadium forming one six-membered and two five-membered chelate rings. The two pyridines are in the equatorial plane. The five atoms in the equatorial plane are nearly coplanar; the vanadium



Scheme 1

† Electronic supplementary information (ESI) available: synthesis of bpaH and $[VO(O_2)(bpaH)ClO_4{\cdot}nH_2O$. See http://www.rsc.org/suppdata/cc/b1/b101010g/

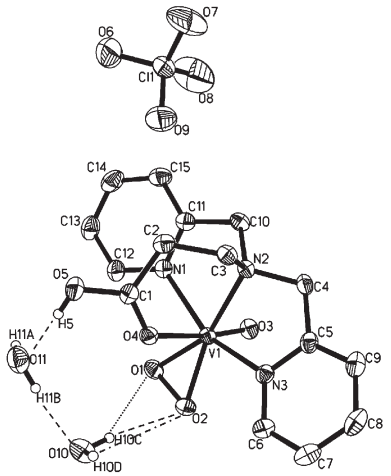


Fig. 2 Molecular structure of $[VO(O_2)bpaH]ClO_4{\cdot}2H_2O$ at the 50% probability level, including the hydrogen bonds (dashed lines). Selected bond lengths (Å) and angles (°): V–O1 1.8734(16), V–O2 1.8827(16), V–O3 1.5877(15), V–O4 2.2095(16), V–N1 2.132(2), V–N2 2.192(2), V–N3 2.133(2), O1–O2 1.422(2), C1–O4 1.222(3), C1–O5 1.302(3), O5–H5 0.8201(10); O1–V–N1 81.68(8), O1–V–O2 44.48(7), O2–V–N3 81.83(8), N1–V–N2 75.53(7), N2–V–N 374.13(7), O3–V–O4 172.25(7). Hydrogen bonds (Å): O1···H10C–O10 3.250, O2···H10C–O10 2.995, O2···H10D–O10 2.806, O5–H5···O11 2.550, O11–H11B···O10 2.711, O11–H11A···O6 (perchlorate) 2.993.

centre is displaced from this plane by 0.2163(8) Å towards the oxo group. The unusual coordination mode of the carboxylic acid function – through the doubly bonded oxygen O4 – has been described previously for a number of dipicolinato complexes of copper,[20] iron[21] and zinc[22] with bond lengths ranging from 2.3 to 2.5 Å (as compared to *ca*. 2.1 Å for the corresponding bond lengths of *de*protonated carboxylic acid functions). The angle O3–V–O4, 172.25°, only slightly deviates from linearity. The bond V–O4 [d = 2.2095(16) Å] is thus surprisingly strong, even more as it is subject to the *trans* effect exerted by the oxo group. It compares to the V–O (carboxylate) distances of 2.144 and 2.045 Å for the carboxylato group *trans* and *cis* to V=O, respectively, in $[VO(L)H_2O(O_2)]^-$ (H_2L = carboxymethylhistidine),[23] d[V–O (carboxylate)] = 2.138 Å for the *trans*-standing carboxylate in $[VO(O_2)(bpg)]$,[9] and d[V-O(carboxylate)] between 2.01 and 2.04 Å in other peroxovanadium complexes containing supporting ligands with *cis*-standing carboxylato functions.[24,25] The complex is the first example of a cationic monoperoxo–oxovanadium complex with an N_3O donor set. Other cationic vanadium complexes which have been described so far contain two NO donor sets ($[VO(O_2)(picolinamide)_2]^+$),[26] or one or two N_2 sets ($[VO(O_2)$-$(phen)(H_2O)_2]^+$;[27] $[VO(O_2)L_2]^+$, L = phen, bipy[28]).

The uncoordinated OH of the carboxylic acid group of $[VO(O_2)(bpaH)]^+$ links a water of crystallisation (O11) *via* a strong hydrogen bond of 2.550 Å, which in turn hydrogen binds to the perchlorate anion and a second water of crystallisation, O10. Two hydrogen bonds of weak to medium strength keep this water in the proximity of the coordinated peroxo group.§ Although only O2 of the peroxide is involved in this H-bonding network to a sizable extent, there are no significant differences in the V–O (peroxide) bond lengths. Bonding parameters [d(V–O1) 1.8734(16), d(V–O2) 1.8827(16) Å; angle O1–V–O2 = 44.48(7)°] are comparable to those in other peroxovanadium complexes;[9,13,23–25,29] the O–O bond length, 1.421(3), is in-between the margins noted for $[V_2O_2(O_2)_4H_2O]^{2-}$ [13] and $[VO(O_2)(tp)(pz)]$ (tp = tris(pyrazolyl)borate, pz = pyrazole).[30]

This special arrangement of carboxylic acid, water and peroxide provides a basis for a mechanism for rapid – and reversible – transfer of a proton to the activated (by coordination to vanadium) peroxo function, and hence a mechanism by which the electrophilicity of this site can be adapted to an appropriate substrate to be oxidised, such as bromide; *cf*. Fig. 1.

Notes and references

‡ *Crystal data*: $C_{15}H_{21}ClN_3O_{11}V$, M = 505.74, monoclinic, space group $C2/c$, a = 31.612(7), b = 7.1835(17), c = 21.290(16) Å, β = 123.274(4)°, V = 4042.1(16) Å^3, T = 293(2) K, Z = 8, μ(Mo-Kα) = 0.69 mm^{-1}. Independent reflections 4382 (R_{int} = 0.0265), final R values [$I > 2\sigma(I_0)$] R_1 = 0.0408, $wR2$ = 0.1005. CCDC 157361. See http://www.rsc.org/suppdata/cc/b1/b101010g/for crystallographic data in .cif or other electronic format.

§ Additional hydrogen bonding contacts exist between the peroxo group and the neighbouring pyridines of the ligand bpaH, *viz*. O1 and H12 (2.749 Å), and O2 and H6 (2.771 Å).

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