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Models of the oxidized forms of polyiron oxo proteins: synthetic routes to (μ-oxo)bis(μ-carboxylato)diiron(III) complexes with neutral monodentate and bidentate capping ligands

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Abstract

Two (μ-oxo)bis(μ-carboxylato)diiron(III) complexes with neutral monodentate and bidentate terminal ligands have been prepared that incorporate features of the diiron oxo centers in the non-heme iron proteins hemerythrin (Hr) and the B2 subunit of ribonucleotide reductase (RRB2) that were not previously modeled. $[Fe_2O(OH_2)_2(O_2CCH_2Cl)_2(bpy)_2](NO_3)_2$ (**1**) and $[Fe_2O(CH_3OH)_2(O_2CCH_3)_2(BIPhMe)_2](NO_3)_2$ (**2**) were synthesized from the appropriate basic iron carboxylate, ferric nitrate and the bidentate nitrogen ligand bpy or BIPhMe. The molecular structures, as determined by X-ray crystallography, and the electronic spectral, Mössbauer and magnetic properties of **1** and **2** reproduce many of the physical properties of the met forms of Hr and RRB2. A singly-bridged (μ-oxo)diiron(III) complex, $[Fe_2O(NO_3)_4(bpy)_2]$ (**3**), was also prepared from ferric nitrate and bpy. The chelating bpy and nitrate ligands afford seven-coordinate ferric centers in the centrosymmetric compound. Complex **3** serves as a synthon for the (μ-oxo)bis(μ-carboxylato)diiron(III) core, for the reaction of **3** with excess chloroacetic acid gives **1**.

Introduction**

Numerous (μ-oxo)bis(μ-carboxylato)diiron(III) complexes with facially coordinating tridentate ligands have been prepared as models for the active site in the protein hemerythrin (Hr) [1–4]. The diferric site of azidometHr, however, contains a monodentate azide ligand which can undergo substitution reactions with a range of halides and pseudohalides [5]. The labile terminal site is necessary for the oxygen transport capabilities of Hr, which in its diferrous state reacts with dioxygen to give a bound hydroperoxide ligand in oxyHr [6, 7]. The diiron centers in ribonucleotide reductase (RR) also contain monodentate terminal ligands, including water, coordinated to both of the ferric ions [8]. In efforts to prepare diiron(III) model complexes with similar reactive terminal sites, the tridentate capping ligands have been replaced with bidentate and monodentate donors. Initial attempts with bidentate nitrogen donors, however, gave only tetranuclear iron complexes, including $[Fe_4O_2(O_2CCH_3)_7\{H_2B(pz)_2\}_2]^-$, and $[Fe_4O_2(O_2CPh)_4(BICO)_2(BICOH)_2]^{2+}$ [9, 10].

An early example of a Hr model complex with bidentate and monodentate terminal ligands, $[Fe_2O(O_2CCH_3)_2(bpy)_2Cl_2]$ was isolated from the reaction of the tetranuclear iron compound, $[Fe_4O_2(O_2CCH_3)_7(bpy)_2](ClO_4)$, with excess bpy and chloride [11, 12]. Several other complexes with monodentate terminal ligands have since been prepared by using a bridging dicarboxylate ligand in place of the two carboxylate bridges [13] and by air oxidation of a diferrous compound [14]. In each of these model compounds the monodentate ligands are anions, chloride or formate ion. In the present study we have identified a new synthetic route to two related complexes, $[Fe_2O(OH_2)_2(O_2CCH_2Cl)_2(bpy)_2](NO_3)_2$ (**1**) and $[Fe_2O(CH_3OH)_2(O_2CCH_3)_2(BIPhMe)_2](NO_3)_2$ (**2**), both of which contain neutral terminal ligands. The synthetic procedure facilitates the incorporation of a variety of different bidentate nitrogen and bridging carboxylate ligands. In addition, a novel seven-coordinate (μ-oxo)diiron(III) complex, $[Fe_2O(NO_3)_4(bpy)_2]$

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**Abbreviations used in this article: BICOH, bis(1-methylimidazol-2-yl)hydroxymethane; BIPhMe, bis(1-methylimidazol-2-yl)phenylmethoxymethane; bpy, 2,2′-dipyridine; 4,4′-Me_2bpy, 4,4′-dimethyl-2,2′-dipyridine; $H_2B(pz)_2^-$, dihydrobis(1-pyrazoyl)borate; EDTA, ethylenediaminetetraacetate; $HB(pz)_3^-$, hydrotris(1-pyrazolyl)borate; phen, 1,10-phenanthroline; H_2DMPP, *m*-phenylenedipropionic acid.

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(3), was prepared. Compound **3** is a precursor to the (μ-oxo)bis(μ-carboxylato)diiron(III) core, as indicated by its reaction with chloroacetic acid to afford **1**. A related investigation has recently been brought to our attention [15].

Experimental

BIPhMe was prepared as described in the literature [14]. All other reagents were used as received. Physical measurements, including X-ray structure determinations, were performed as previously outlined [16, 17].

Basic iron acetate and the chloroacetate analogue, $[Fe_3O(O_2CR)_6(H_2O)_3](NO_3)$ where $R = CH_3$ or CH_2Cl, were prepared by allowing $Fe(NO_3)_3 \cdot 9H_2O$ to react for several hours with a large excess of the carboxylic acid in boiling water. Slow evaporation gave large red crystals of both derivatives in greater than 70% yield [18].

The reaction of the basic iron chloroacetate with one equivalent of ferric nitrate and four equivalents of bpy in acetonitrile gave a dark green slurry. Filtration of the reaction mixture followed by slow evaporation afforded green crystals of **1** in approximately 25% yield. A similar reaction with basic iron acetate, ferric nitrate and BIPhMe in methanol afforded a dark green solution. Vapor diffusion of diethyl ether into the reaction mixture gave in 70% yield crystals of **2**·MeOH, which lose solvent rapidly in air. *Anal.* Calc. for **1**, $C_{24}H_{24}N_6O_{13}Cl_2Fe_2$: C, 36.63; H, 3.07; N, 10.68; Cl 9.01; Fe, 14.19. Found: C, 36.83; H, 3.01; N, 10.68; Cl, 9.20; Fe, 14.01%. *Anal.* Calc. for **2**, $C_{38}H_{50}N_{10}O_{15}Fe_2$: C, 45.71; H, 5.05; N, 14.03. Found: C, 45.39; H, 4.74; N, 14.45%. Electronic spectral, Mössbauer, and magnetic properties for **1** and **2** are listed in Table 1. Crystal data for **1**: triclinic, space group $P\bar{1}$, $a = 9.935(2)$, $b = 18.286(2)$, $c = 9.358(1)$ Å, $\alpha = 91.65(1)$, $\beta = 117.85(1)$, $\gamma = 87.13(1)°$, $Z = 2$, $V = 1501.3(5)$ Å^3. For 4639 unique observed reflections collected at −38 °C with $F^2 > 3\sigma(F^2)$, $R = 0.036$ and $R_w = 0.056$. Crystal data for **2**·MeOH: triclinic, space group $P\bar{1}$, $a = 12.034(2)$, $b = 13.838(1)$, $c = 15.902(4)$ Å, $\alpha = 103.65(1)$, $\beta = 103.63(1)$, $\gamma = 105.59(1)°$, $Z = 2$, $V = 2348.8(8)$ Å^3. For 5559 unique observed reflections collected at −74 °C with $F^2 > 3\sigma(F^2)$, $R = 0.077$ and $R_w = 0.107$.

The reaction of ferric nitrate with one equivalent of bpy in acetonitrile afforded red microcrystals of **3** after several hours in approximately 30% yield. *Anal.* Calc. for **3**, $C_{20}H_{16}N_8O_{13}Fe_2$: C, 34.91; H, 2.34; N, 16.29; Fe, 16.23. Found: C, 35.01; H, 2.30; N, 16.44; Fe, 16.46%. Magnetic and spectral properties of **3** are as follows: ν_s(Fe–O–Fe), 393 cm^{-1}; antiferromagnetic exchange coupling, $-J = 101$ cm^{-1}; Mössbauer spectrum, $\delta = 0.56$ mm s^{-1}, $\Delta E_Q = 2.10$ mm s^{-1}. Crystal data for **3**: mono-

TABLE 1. Comparison of electronic and magnetic properties of compounds **1** and **2** with selected (μ-oxo)bis(μ-carboxylato)diiron(III) model compounds and proteins[a]

	1	**2**	**4**	**5**	**6**	**7**	$metN_3Hr$	metRRB2
λ_{max} (nm)	336 (sh)	c	329 (6060)	328 (sh)	341 (3000)	329 (3400)	326 (3375)	325 (2350)[d]
(ϵ/Fe, cm^{-1} mol^{-1} l)[b]	368 (sh)			365 (sh)	360 (sh)	354 (sh, 2900)	380 (sh, 2150)	370 (1800)
	454 (400)		464 (sh, 387)	462 (450)		448 (370)	446 (1850)	
	497 (sh, 325)			483 (400)	483 (400)	478 (sh, 340)		500 (200)
	538 (sh)			535 (sh)	525 (sh)	520 (sh)	530 (sh)	
	667 (60)			655 (70)	682 (90)	662 (70)	680 (95)	600 (75)
ν_s(Fe–O–Fe) (cm^{-1})[e]	536	527	f	532	522	520	507	493
$-J$ (cm^{-1})[g]	126	113	132	119	122	111	134[h]	108
δ (mm s^{-1})[i]	0.52	0.53	0.37	0.51	0.52	0.54	0.50	0.53, 0.44
ΔE_Q (mm s^{-1})	1.89	1.80	1.80	1.66	1.94	1.81	1.90	1.65, 2.45
Reference	j	j	11	13	13	14	7, 19–21	20, 22, 23

[a] **1**, $[Fe_2O(OH_2)_2(O_2CCH_2Cl)_2(bpy)_2](NO_3)_2$; **2**, $[Fe_2O(CH_3OH)_2(O_2CCH_3)_2(BIPhMe)_2](NO_3)_2$; **4**, $[Fe_2OCl_2(O_2CCH_3)_2(bpy)_2]$; **5**, $[Fe_2OCl_2(MPDP)(4,4'\text{-}Me_2bpy)_2]$; **6**, $[Fe_2OCl_2(MPDP)(BIPhMe)_2]$; **7**, $[Fe_2O(O_2CH)_4(BIPhMe)_2]$. [b] Reported for CH_2Cl_2 (**1**, **4** and **5**) and $CHCl_3$ (**6** and **7**) solutions. [c] Not measured. [d] The extinction coefficients listed are one-half the magnitude of those reported in ref. 23. See ref. 2 for a discussion. [e] Spectra for **1**–**3** were measured in a KBr matrix, and, for **7**, in a $CHCl_3$ solution by using 406.7 nm Kr^+ laser excitation; data were collected for **5** in CH_2Cl_2, and for **6** in $CHCl_3$ solutions with 514.5 nm Ar^+ laser excitation. [f] Not reported. [g] Magnetic measurements and fitting procedures were performed as described in ref. 16. [h] Measured for metHr. [i] Mössbauer spectra were collected at 4.2 K. [j] This work.

clinic, space group $P2_1/n$, $a=9.2477(8)$, $b=12.876(2)$, $c=10.992(2)$ Å, $\beta=97.02(1)°$, $Z=2$, $V=1299.1(3)$ Å^3. For 2172 unique observed reflections collected at −72 °C with $F^2>3\sigma(F^2)$, $R=0.031$ and $R_w=0.039$.

Results and discussion

Compounds 1 and 2 were prepared as outlined in eqn. (1).

$$[Fe_3O(O_2CR)_6(H_2O)_3](NO_3)+Fe(NO_3)_3\cdot 9H_2O+4B \longrightarrow$$
$$2[Fe_2O(L)_2(O_2CR)_2(B)_2](NO_3)_2+2HO_2CR \quad (1)$$

1: $L=H_2O$, B = bpy, $R=CH_2Cl$
2: $L=CH_3OH$, B = BIPhMe, $R=CH_3$

Their structures were determined by X-ray crystallography, and an ORTEP drawing of 1 is shown in Fig. 1. The two compounds contain the (μ-oxo)bis(μ-carboxylato)diiron(III) core found in metHr, with terminal monodentate and bidentate bpy or BIPhMe ligands completing the distorted octahedral coordination sphere of each iron atom. The structure of a related Mn(III) dimer with terminal water ligands has been reported [24]. The monodentate ligands in 1 and 2 are positioned *cis* to the bridging oxo group, as observed for the exogenous ligand binding site in metHr. These terminal ligands are in an *anti* arrangement with respect to the Fe–O–Fe plane, like the chloride and formate ligands in related model complexes [11, 13, 14]. There is a noticeable lengthening in the Fe–$O_{COO\mathit{trans}}$ bonds *trans* to the water or methanol ligands, which is also observed for the carboxylate oxygen atom *trans* to the azide ion in metmyoN_3Hr (see Table 2) [25]. The nitrogen ligands *trans* to the bridging oxo group experience a similar elongation. A comparison of the structural parameters of 1 and 2 reveals a slightly expanded diiron core for 2, with longer Fe–μ-oxo bonds, a larger iron–iron separation, and a larger Fe–O–Fe angle.

TABLE 2. Selected interatomic distances (Å) and angles (°) for compounds 1 and 2 and metN_3myoHr[a]

	1	2	metN_3myoHr[b]
Fe–μ-O	1.782(2)	1.798(5)	1.77
	1.785(2)	1.802(5)	1.80
Fe–O(H)R	2.083(2)	2.103(5)	
	2.098(2)	2.118(5)	
	(R = H)	(R = CH_3)	
Fe–N_{cis} (av.)	2.121(2)	2.116(6)	2.13
Fe–N_{trans} (av.)	2.183(2)	2.174(6)	2.24
Fe–O_{COO} (av.)	2.064(2)	2.038(5)	2.10
Fe–$O_{COO\mathit{trans}}$ (av.)	2.110(2)	2.049(5)	2.18
Fe–$O_{COO\mathit{cis}}$ (av.)	2.018(2)	2.028(5)	2.05
Fe···Fe	3.1109(5)	3.167(2)	3.23
Fe–O–Fe	121.5(1)	123.2(3)	130

[a] Fe–$N_{\mathit{cis/trans}}$ describes iron–nitrogen bonds *cis* or *trans* to the bridging oxo ligand. Fe–$O_{COO\mathit{cis/trans}}$ describes iron–oxygen bonds of a bridging carboxylate *cis* or *trans* to the monodentate oxygen ligand (H_2O in 1 and CH_3OH in 2). [b] Ref. 25.

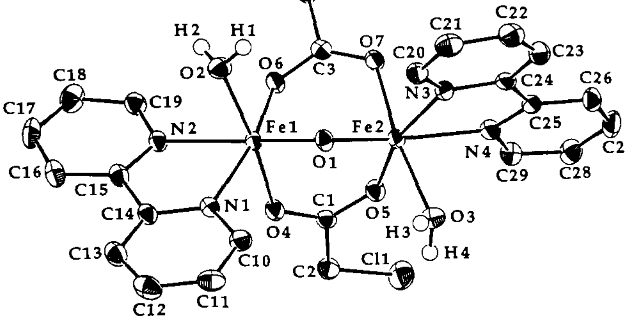

Fig. 1. ORTEP drawing of the dication in 1 showing 50% thermal ellipsoids. Hydrogen atoms were omitted for clarity, except for those of the bound water molecules, which were drawn as open spheres.

The physical properties of compounds 1 and 2 reproduce many of the characteristic features of metN_3Hr [7, 19–21] and metRRB2 (see Table 2) [22, 23]. Compound 1 exhibits a low energy transition in its electronic spectrum at 667 nm, which is blue shifted by comparison to the spectra of compounds having all nitrogen donor capping ligands [16, 26, 27]. The electronic spectral parameters of complex 2 could not be measured since in solution it appears to be in equilibrium with various other species. The energy of the symmetric stretch ν_s(Fe–O–Fe) and antiferromagnetic exchange coupling constants measured in the solid-state for 2 are slightly lower than those determined for 1, owing to the larger Fe–O–Fe angle and longer Fe–μ–oxo bonds [28, 29]. These properties of 1 and 2 have been observed in model complexes with either tridentate or a combination of bidentate and monodentate ligands.

A third (μ-oxo)diiron(III) compound was prepared from the reaction of ferric nitrate with bpy in acetonitrile. The structure of 3 as determined by X-ray crystallography is depicted in Fig. 2. The bridging oxo atom lies on a crystallographically imposed center of symmetry. The two ferric ions are seven-coordinate, with an oxo bridge, one bpy, and two chelating nitrates as ligands. The μ-oxo and one nitrogen atom of the bpy ligand occupy the axial positions of the distorted pentagonal bipyramid, with the second nitrogen atom of the bpy ligand and the four oxygen donors of the chelating nitrates lying in the equatorial plane. A related compound having the formula $[Fe_2O(H_2O)_6(phen)_2](NO_3)_4$ has been isolated from aqueous solution and structurally characterized. The water molecules in this complex occupy the sites containing the nitrate ligands in 3,

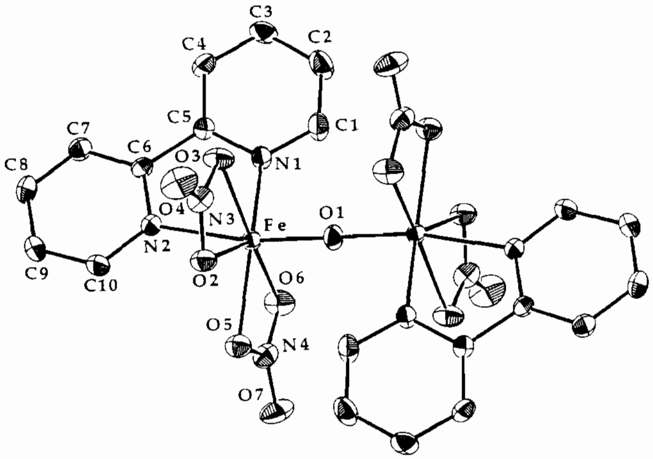

Fig. 2. ORTEP drawing of **3** with 50% thermal ellipsoids. Hydrogen atoms were omitted for clarity. Selected bond distances (Å) and angles (°) are as follows: Fe–O(1) 1.7755(4), Fe–O(2) 2.159(2), Fe–O(3) 2.262(2), Fe–O(5) 2.142(2), Fe–O(6), 2.203(2), Fe–N(1) 2.140(2), Fe–N(2) 2.178(2), N(3)–O(2) 1.284(3), N(3)–O(3) 1.264(3), N(3)–O(4) 1.214(3), N(4)–O(5) 1.278(3), N(4)–O(6) 1.273(3), N(4)–O(7) 1.213(3), Fe–O(1)–Fe 180, O(1)–Fe–O(2) 96.32(5), O(1)–Fe–O(3) 91.19(5), O(1)–Fe–O(5) 98.67(5), O(1)–Fe–O(6) 93.44(6), O(1)–Fe–N(1) 95.31(6), O(1)–Fe–N(2) 169.19(6), O(2)–Fe–O(3) 57.97(7), O(5)–Fe–O(6) 59.01(7), O(2)–Fe–O(5) 75.09(7), O(3)–Fe–N(1) 79.84(8), O(6)–Fe–N(1) 86.92(8), N(1)–Fe–N(2) 75.02(8), Fe···Fe 3.5510(7).

resulting in six coordination for the two ferric ions [30]. A few seven-coordinate iron compounds, including EDTA derivatives [31], have been prepared, and chelating nitrate ligands coordinated to ferric ions also have literature precedents [32]. The symmetric stretch, ν_s(Fe–O–Fe), antiferromagnetic exchange coupling constant and Mössbauer parameters for **3** agree with values reported for other linear (μ-oxo)diiron(III) compounds [4].

Compound **3** proved to be a useful precursor for the preparation of complexes having the (μ-oxo)bis(μ-carboxylato)diiron(III) core. Reaction of **3** with an excess of chloroacetic acid in acetonitrile gave green crystals of **1** in 30% yield upon slow evaporation.

In conclusion, new routes to model complexes of the metal centers in dinuclear iron oxo proteins have been developed. Compounds **1** and **2** have spectroscopic and magnetic properties similar to those of the proteins metHr and metRRB2, and are the first to contain neutral, monodentate ligands. An unusual seven-coordinate (μ-oxo)diiron(III) compound, which serves as a synthon for metHr core models, has also been characterized.

Supplementary material

IR spectroscopic data and tables of atomic positional and thermal parameters for **1**–**3** and an ORTEP drawing of **2** are available from the authors.

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