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Biomimetic Synthesis

An Iron(III) Iodosylbenzene Complex: A Masked Non-Heme $Fe^{V}O$**

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Iodosylarenes are an important class of oxygen atom transfer reagents in organic synthesis, and they are often used in conjunction with transition-metal-based catalysts.[1–3] These are most commonly iron[4–7] and manganese[8–11] porphyrin, Mn-corrole,[12] Mn-corrolazinato,[13,14] and Mn-salen complexes,[15] and even cytochrome P450.[16] Hypervalent metal–oxo complexes that relay the oxygen atom from the iodosylarene donor to the substrate acceptor are most commonly invoked as the active oxidants in these catalytic mechanisms. Accordingly iodsosylarenes have been used in the preparation of hypervalent metal–oxo complexes. No metal-complexed iodosylarene has been structurally characterized in the solid state; however, the isolation of a reactive iodosylbenzene complex of Mn-porphyrin was reported nearly 30 years ago.[17]

Oxygen atom transfer from iodosylarenes to LM^{n+} complexes give the corresponding $LM^{(n+2)+}O$ species (or $L^{\bullet +}M^{(n+1)+}O$ if the ligand is non-innocent, for example when L = porphyrin) [Equation (1), steps i + ii]. Occasionally, intervening transient species assigned to metal–iodosylarene adducts have been spectroscopically identified in these types of reactions. More or less unstable $Mn^{V}O$ porphyrin[8] and salen[13,18,19] systems, $Cr^{V}O$,[20] $[(porph^{\bullet})Fe^{IV}O]^{+}$[6,7] systems, and $[Fe^{IV}O(tmc)]^{2+}$[21] (tmc = tetramethylcyclam) have been accessed by oxygen atom transfer from iodosylbenzene to the appropriate Mn^{III}, Cr^{III}, Fe^{III}, and Fe^{II} precursors respectively. Recently, a novel $Co^{IV}O$ solution species was generated at −60 °C by the reaction of 2-(*tert*-butylsulfonyl)iodosylbenzene with $[Co^{II}(TMG_3tren)(OTf)]^{+}$.[22] Nam et al. have demonstrated the back-reaction of the equilibrium ii in Equation (1) by formation of a spectrosopically detected species assigned to $[(porph)Fe^{III}(OIPh)]^{+}$ from the reaction of $[(porph^{\bullet})Fe^{IV}O]^{+}$ with iodobenzene.[6]

$$[LM^{n+}] + OIAr \overset{i}{\rightleftharpoons} [LM^{n+}OIAr] \overset{ii}{\rightleftharpoons} [LM^{(n+2)+}O] + IAr \tag{1}$$

By using the monoanionic hexadentate ligand *N,N,N′*-tris(2-pyridylmethyl)ethylendiamine-*N′*-acetate ($tpena^{-}$), we describe herein the structural characterization of a reactive high-spin seven-coordinate iron(III) complex, $[(tpena)Fe(OIC_6H_5)]^{2+}$ (**1**), which contains an auxiliary iodosylbenzene ligand. Complex **1** is prepared by dissolving the oxo-bridged complex $[(tpenaH)Fe(\mu\text{-}O)Fe(tpenaH)]^{4+}$ (**2**) in acetonitrile to form $[Fe^{III}(tpena)]^{2+}$ (**3**) [Equation (2)], which then reacts with iodosylbenzene to give **1** [Equation (3)]. Dehydration and oxo bridge cleavage of **2** seems particularly facilitated by $tpena^{-}$ by comparison to most other oxo-bridged diiron(III) species, which are typically more robust in solution.[23,24] The uncoordinated basic pyridyl groups may be playing an active role in this process. If protonated, as is found in the crystal structure (see below), a dehydration reaction is formally intramolecular. Thus solutions of **2** turn red within minutes owing to the formation of **3**, which has been characterized by ESI-MS, UV/Vis, and ESR spectroscopy.[25] The crystal structure of the Co^{III} analogue of **3** is known.[26] ESR spectra show a rhombic signal centered at $g = 2$ that indicates that **3** contains low-spin iron (III).

$$[(tpenaH)Fe(\mu\text{-}O)Fe(tpenaH)]^{4+}\ (\mathbf{2}) \rightarrow 2[Fe^{III}(tpena)]^{2+}\ (\mathbf{3}) + H_2O \tag{2}$$

$$[Fe^{III}(tpena)]^{2+}\ (\mathbf{3}) + OIPh \rightarrow [Fe^{III}(tpena)OIPh]^{2+}\ (\mathbf{1}) \tag{3}$$

Complex **1** was isolated in the solid state as the perchlorate salt. Other solvents and counteranions tested either did not give **1** or promoted rapid decomposition. Samples of $\mathbf{1}(ClO_4)_2(MeCN)(H_2O)_{0.5}$ may be stored for a few days at −40 °C. Figure 1 shows the structures of **1** and **2**. The iron atoms of **1** are seven-coordinate with an approximately pentagonal bipyramidal geometry containing *trans*-orientated pyridine donors in the apical positions. The Fe−OIPh distance is 1.933(3) Å (average).[27] This is shorter than the Fe−$O_{carboxylate}$ at 2.105(4) Å (av.). As these *cis*-orientated oxygen donors are both located in the pentagonal plane and neither are under the influence of any particular *trans* effect, the Fe−O distances are noteworthy, given that the terminal carboxylato and iodosylbenzene are negatively charged and neutral, respectively. The iodosyl O−I distance in **1** (av. 1.920(3) Å) is longer by approximately 0.071 Å and the C−I distance (av. 2.094(5) Å) shorter by 0.03 Å compared with the corresponding distances in 1-(*tert*-butylsulfonyl)-2-iodosylbenzene.[28] As alluded to above, an interesting feature of the μ-oxodiiron complex **2** is that one pyridine arm of each ligand is decoordinated and protonated. The protonated pyridines are H-bonded to the non-coordinated carboxylate oxygen atom of the $tpena^{-}$ ligand bound to the adjacent iron atom.

The solid- and solution-state ESR spectra of **1** are identical and show a broad axial signal at approximately $g = 4.5$, which is consistent with high-spin Fe^{III}. A comparison of the IR spectra of **1**, **2**, and PhIO is instructive. The bands assigned to $\nu_{Fe\text{-}O\text{-}Fe}$ at 836 cm^{-1} in **2** and 493 cm^{-1} assigned to I−O···I vibrations in solid polymeric PhIO[29] are both absent in **1**; however, it is not possible to pick a distinctive band that

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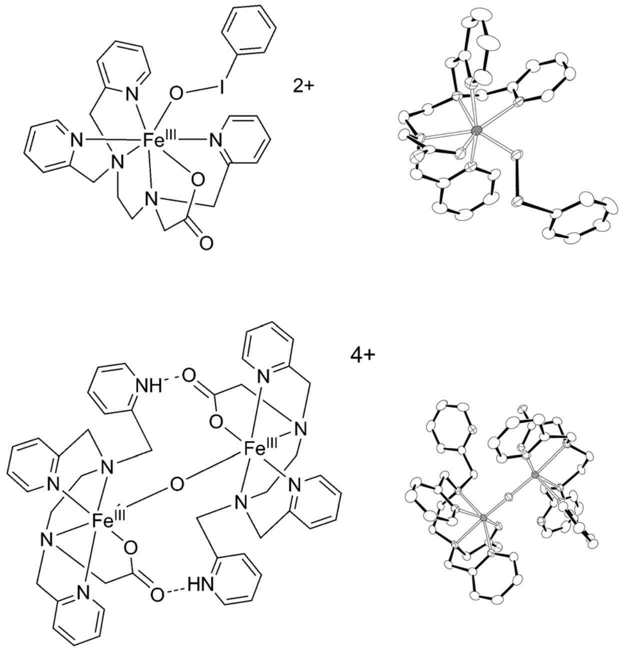
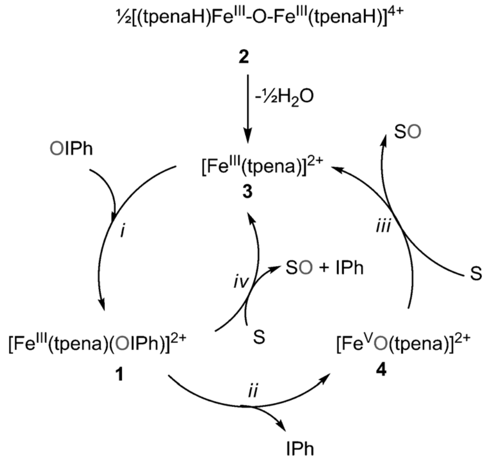


Figure 1. Diagrams and the single-crystal X-ray structures of **1** (top) and **2** (bottom) in $\mathbf{1}(\mathrm{ClO_4})_2(\mathrm{MeCN})(\mathrm{H_2O})_{0.5}$ and $\mathbf{2}(\mathrm{ClO_4})_4(\mathrm{H_2O})_2$. Ellipsoids are set at 50% probability, hydrogen atoms omitted for clarity; for important bond lengths and angles, see the text and the Supporting Information.



Scheme 1. Formation of the Fe$^{\mathrm{III}}$ species **3** and the catalysis of the oxidation of a substrate (denoted "S") by iodosylbenzene. See text for details using thioanisole.

might be due to the iodosylbenzene ligand. ESR and UV/Vis spectroscopy show that **1** remains intact for a few hours at room temperature upon dissolution in acetonitrile. The ESI mass spectrum ($\mathrm{CH_3CN}$) of $\mathbf{1}(\mathrm{ClO_4})_2(\mathrm{MeCN})(\mathrm{H_2O})_{0.5}$ shows an ion at m/z 765, which can be assigned to $[\mathrm{Fe^{III}(tpena)(OIC_6H_5)(ClO_4)}]^+$; this ion is present in variable amounts, which is consistent with its instability.

The addition of solid $\mathbf{1}(\mathrm{ClO_4})_2(\mathrm{MeCN})(\mathrm{H_2O})_{0.5}$ to a $\mathrm{CH_3CN}$ solution containing equimolar amounts of thioanisole at room temprature results in conversion of approximately 0.5 equivalents of the thioanisole to methylphenylsulfoxide within 1.5 h and the emergence of the ESR signal that is due to **3**. This reaction can be used for catalysis. Thus at 50 °C in acetonitrile, 850 turnovers over 2 h were measured using of **2** as the pro-catalyst in reactions containing **3**/thioanisole/iodosylbenzene in a ratio of 1:1000:1000. Under these conditions, the iodosylbenzene is not fully dissolved until the reaction is complete. The addition of a further 1000 equivalents each of iodosylbenzene and thioanisole resulted in an equally efficient yield of a second crop. Thus a TON of 1588 has been measured with no indication of catalyst decomposition. Under these conditions, iodosylbenzene does not oxygenate thioanisole in the absence of a catalyst. The solvent systems available for using the Fe–tpena$^-$ system may however be rather limited: The presence of water will lead to the regeneration of **2** and a lack of catalytic activity. As mentioned regarding the synthesis of **1**, other solvents and counteranions annihilate **1**; similarly, these inhibit catalytic activity.

Is the active metal-based oxo transfer reagent complex **1** or is it a Fe$^{\mathrm{V}}$ perferryl species, $[\mathrm{Fe^V(O)(tpena)}]^{2+}$ (**4**) derived by unmasking **1**, according to Equation (1)? Two proposals are illustrated in Scheme 1. Steps i and iv constitute the option of **1** as the active oxidant, while steps i, ii, and iii represent our favored option of **4** as the active oxidant. While **1**, **2**, and **3** are well-characterized, we could not spectroscopically observe **4**.[30] We speculate that the decomposition of **1** to give the extremely reactive **4** may be rate-limiting in this reaction. In a more general context, one of Halpern's guidelines[31] for catalysis is that species that can be detected under turnover conditions are generally not part of the catalytic cycle, but rather labile reservoirs, in equilibrium with the true active species. This guideline can be applied readily to the cycle in Scheme 1 containing **4**. The d^3 system of the putative species **4** will prefer a more regular octahedral coordination requiring decoordination of one pyridyl arm of tpena$^-$ (as in **2**); perhaps Fe$-$N$_{\mathrm{py}}$ cleavage is concurrent with the I$-$O bond cleavage, or one triggers the other. It is noteworthy that the appropriate trends in O$-$I, Fe$-$O, and I$-$C bond lengths for facilitating I$-$O cleavage to give **4** are found in the structure of **1**.

Whether a $\mathrm{LM}^{n+}\mathrm{OIAr}$ or a $\mathrm{LM}^{(n+2)+}\mathrm{O}$ species is the active oxidant has been considered previously for other metal-catalyzed iodosylbenzene oxidations. Nam and co-workers have determined that $[(\mathrm{porph}^{\bullet})\mathrm{Fe^{IV}O}]^+$ [equivalent to the generic $[\mathrm{LM}^{(n+2)+}\mathrm{O}]$ in Eq. (1)], and not $[(\mathrm{porph})\mathrm{Fe^{III}(OIPh)}]^+$, is the active oxidant.[7] In contrast, Goldberg and co-workers ruled out a corresponding Mn$^{\mathrm{V}}$O–corrolazine species as the active oxidant in oxygen atom transfer but rather that it is the oxygen atom in PhIO coordinated to Mn$^{\mathrm{III}}$ that is transferred to the substrate in a concerted mechanism.[13] Neither of these examples are particularly pertinent to the present case in terms of the redox non-innocence of the supporting ligands and the metal ion in the second case, so neither can be used to predict one or other of the corresponding alternate pathways depicted by in Scheme 1 for the Fe–tpena$^-$ system. We note however that it is overwhelmingly the hypervalent metal–oxo species generated according to Equation (1) that are proposed to be the active oxidants in oxidations using iodosylarenes as the terminal oxygen atom donor. At this stage, we believe that there is nothing to suggest that this will not be the case also for the Fe-tpena$^-$ system and that **4** is the active oxidant. Thus **1** can be considered to be a labile reservoir for **4**: A chemically masked non-heme Fe^{V}O species.

The iron-tpena$^-$ is at first sight surprising in its ability to stabilize the first isolated iodosylbenzene complex and likewise an unmasked Fe^{V}O derivative, as accessible coordination sites for the auxiliary OIC_6H_5 and O^{2-} ligands might be envisaged to be impeded by this potentially hexadentate ligand. The structures of the Fe^{III} complexes **1** and **2** quell this argument: In **1**, the ligand acts as a hexadentate ligand; however, an additional metal binding site is available because of sevenfold coordination. In **2**, the iron atom is six-coordinate; however, one pyridine arm is decoordinated. Thus the structures of **1** and **2** incarnate biomimetic active site multifunctionality: the iron-tpena$^-$ system supports: 1) a metal-based oxidant; 2) coordinative flexibility; and 3) a donor arm that can coordinate and decoordinate. Further, when decoordinated, the pyridyl group potentially serves dual functions: It can act as a proximal internal base, and it may even serve to stabilize an electrophilic oxyl group through an intramolecular interaction. Fe^{V}O species have been proposed as the O_2-derived metal-based oxidants in biological oxidation reactions that are reliant on mononuclear non-heme iron enzymes.[32] These typically incorporate at least one terminal carboxylate donor, such as the tpena$^-$ system. Thus tpena$^-$ mimics the so-called N_2O triad. The extra three neutral N donors of the hexadentate tpena$^-$ serve not only to prevent oligomerization reactions, they actively participate in the structures and reactivity in ways reminiscent of the roles often proposed for proximal basic amino acids at metalloenzyme active sites.

In summary, we have structurally characterized the first iodosylarene metal complex as a seven-coordinate iron(III) complex. Its catalytic reactivity in the perspective of commonly accepted mechanisms suggests that it can be described as a relatively stable chemically masked non-heme Fe^{V}O species. Similarly, a tertiary amine N donor of a multidentate ligand in a Fe^{III} complex has been shown to mask its perferryl tautomer: $Fe^{III}–O–NR_3 \leftrightarrow Fe^{V}(O)(NR_3)$.[33] The putative dicationic species **4** must contain a more electrophilic oxyl group than the Fe^{V}O complex of the macrocyclic tetraamido ligand, TAML, $[Fe(TAML)(O)]^-$ which was spectroscopically characterised by de Oliveira et al.[34] The implication in the isolation of more hypervalent oxyl complexes is that equilibrium ii in Equation (1) between the reactive $LM^{n+}OIAr$ and $LM^{(n+2)+}O$ species apparently usually lies to the right-hand side. Our observations using the non-heme type Fe–tpena$^-$ suggests that the same equilibrium lies to the left-hand side. A variety of supporting multidentate chelating ligands and metal ions have been used reactions that are summarized by Equation (1), and the Fe-tpena$^-$ system stands out in two ways: 1) its coordinative flexibility, and 2) the overall positive charge of the putative Fe^{V}oxo species, which is one unit higher compared to the corresponding porphyrin and salen systems and two higher compared to corrolazine systems most commonly associated with this sort of chemistry. These findings are consistent with the formation of a more electrophilic perferryl species and a potentially better oxygen atom relay catalyst.

Experimental Section

1$(ClO_4)_2(MeCN)(H_2O)_{0.5}$: **2**$(ClO_4)_4(H_2O)_2$[19] (45 mg, 0.050 mmol) was dissolved in acetonitrile (4 mL) and iodosylbenzene (22 mg, 0.10 mmol) was added. The mixture was stirred for 30 min until a clear red solution was obtained. Diethyl ether (8 mL) was added, and an orange powder precipitated. This precipitate was collected and dried in a stream of nitrogen to give **1**$(ClO_4)_2(MeCN)(H_2O)_{0.5}$ as an orange-red powder. Yield: 86 mg (94%). Elemental analysis (%) calcd for **1**$(ClO_4)_2(MeCN)_{0.5}(H_2O)_{0.5}$ ($Fe_2C_{58}H_{63}I_2Cl_4N_{11}O_{23}$): C 38.91, H 3.55, N 8.61; found: C 38.82, H 3.37, N 8.87. IR spectroscopy: $\tilde{\nu}=$ 3552 (br), 3084 (m), 1600 (s), 1571 (m), 1470 (m), 1440 (m), 1389 (m), 1297 (w), 1192 (w), 1067 (s), 993 (m), 947 (m), 865 (w), 834 8w), 765 (m), 743 (m), 679 (m), 650 8 m), 619 (s), 529 (w), 490 cm^{-1} (w). UV/Vis (CH_3CN): 422 nm, (sh, 1.1×10^3 $L\,mol^{-1}\,cm^{-1}$). ESIMS (CH_3CN): m/z 765.0071 (15%, $[Fe^{III}(tpena)(OIPh)(ClO_4)]^+$). ESR, UV/Vis, IR, and ESIM spectra of **1**, **2**, and **3**, and details of oxidation reactions and structure determinations are given in the Supporting Information.

Crystals of **1**$(ClO_4)_2(MeCN)(H_2O)_{0.5}$ suitable for X-ray diffraction were obtained by the slow evaporation of a concentrated solution of **1**$(ClO_4)_2$ in acetonitrile at 4°C.CCDC 864721 (**1**) and CCDC 864722 (**2**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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