**Coordination Chemistry | Hot Paper**

**Directing a Non-Heme Iron(III)-Hydroperoxide Species on a Trifurcated Reactivity Pathway**

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In memory of Professor John J. McGarvey

Abstract: The reactivity of $[\text{Fe}^{III}(\text{tpena})]^2^+$ ($\text{tpena} = \text{N,N,N'-tris(2-pyridylmethyl)ethylenediamine-N'-acetate}$) as a catalyst for oxidation reactions depends on its ratio to the terminal oxidant H$_2$O$_2$ and presence or absence of sacrificial substrates. The outcome can be switched between: 1) catalysed H$_2$O$_2$ disproportionation, 2) selective catalytic oxidation of methanol or benzyl alcohol to the corresponding aldehyde, or 3) oxidative decomposition of the tpena ligand. A common mechanism is proposed involving homolytic O–O cleavage in the detected transient purple low-spin ($S = \frac{1}{2}$) ([tpenaH]Fe$^{III}$O=O–OH)$^{1+}$. The resultant iron(IV) oxo and hydroxyl radical both participate in controllable hydrogen-atom transfer (HAT) reactions. Consistent with the presence of a weaker o-donor carboxylate ligand, the most pronounced difference in the spectroscopic properties of $[\text{Fe}(\text{OOH})-(\text{tpenaH})]^2^+$ and its conjugate base, $[\text{Fe}(\text{OO})\text{tpenaH}]^{1+}$, compared to non-heme iron(III) peroxide analogues supported by neutral multidentate N-only ligands, are slightly blue-shifted maxima of the visible absorption band assigned to ligand-to-metal charge-transfer (LMCT) transitions and, corroborating this, lower Fe$^{III}$/Fe$^I$ redox potentials for the pro-catalysts.

**Introduction**

Oxygen-coordinated iron complexes, such as iron(II)-O$_2$ (dioxygen), iron(III)-O$_2$ (superoxo and peroxido), iron(III)-OOH (hydroperoxido), and iron(III)-OOH (alkylperoxido), along with high-valent iron(IV) and iron(V) oxides formed upon homolytic or heterolytic cleavage of the O–O bond in these complexes, have been proposed as key catalytically competent intermediates in oxidations catalysed by heme$^{1,2}$ and non-heme$^{3,4,6-8}$ enzymes, as well as in synthetic model compounds.$^{3,4,6-8}$ To date, the field of non-heme peroxido compounds has been largely dominated by systems employing neutral aminopyridyl chelating ligands.$^{6,8}$ However, akin to the modulation of O$_2$ activation by heme enzymes mediated by a donor ligand trans to the oxygen binding site, we can reasonably expect that the introduction of anionic oxygen donors into the coordination sphere of an iron ion will stabilize higher oxidation states. Concomitantly, the O–O bond of peroxido ligands coordinated to the same iron centre will be weakened. This hypothesis is supported by the fact that many oxidation processes catalysed by non-heme iron O$_2$-activating enzymes, such as Rieske dioxygenases, tetrahydropterin-dependent hydroxylases, and 2-oxoglutarate-dependent dioxygenases and hydroxylases, possess an active site consisting of two histidine residues and one carboxylate group from Asp or Glu (Scheme 1). The reaction pathways followed by these enzymes proceed through cleavage of the O–O bond of peroxide/superoxide ligands derived from O$_2$ to form high-valent iron-oxido species, followed by direct oxidation of a substrate by the generated non-heme iron(IV).$^{4,8}$ Despite the biological precedence, the weakening of the O–O bond of an iron-coordinated peroxido ligand by the proximity of a carboxylato group has, to our knowledge, not yet been evaluated through systematic studies in model complexes.

Iron(III)-hydroperoxido and -peroxido complexes based on neutral pentadentate (NS) aminopoly pyridyl ligands with an ethylenediamine backbone as the supporting scaffold, N-alkyl N,N'-tris(2-pyridylmethyl)ethylenediamine (Rtpen; Scheme 2a) were the first systems for which peroxide derivatives were spectroscopically characterized, and these have been extensively studied.$^{10-18}$ Typically, these are generated by the reaction of air-stable iron(II) precursor complexes with H$_2$O$_2$, a prerequisite for which is oxidation of the iron centre from the Fe$^{II}$ to the Fe$^{III}$ oxidation state prior to formation of the Fe$^{III}$-OOH...

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Results and Discussion

Fe\textsuperscript{II}/Fe\textsuperscript{III} redox potentials for analogous iron complexes of N5O and N6 ligands

Solutions of [Fe\textsuperscript{II}(tpena)]\textsuperscript{2+} in acetonitrile are obtained by the dehydration of [[tpenaH]Fe(μ-O)Fe(tpenaH)]\textsuperscript{4+} upon dissolution.\textsuperscript{[21]} [[tpenaH]Fe(μ-O)Fe(tpenaH)]\textsuperscript{4+} → 2 [Fe(tpena)]\textsuperscript{2+} + H\textsubscript{2}O.

The cyclic voltammogram of [Fe\textsuperscript{II}(tpena)]\textsuperscript{2+} in acetonitrile shows a broad wave due to overlapping reversible Fe\textsuperscript{III}/Fe\textsuperscript{II} redox couples at 0.02 V and 0.06 V vsFc/Fc\textsuperscript{+} (Figure 1 a). The redox waves are associated with the high-spin (S = 5/2) mer-py3-Fe(tpena)]\textsuperscript{2+/3+} and low-spin (S = 1/2) fac-py3-Fe(tpena)]\textsuperscript{2+/3+} diastereoisomers (Figure 1 b). Both the mer-py3 and fac-py3 isomers have been previously identified in both the solid and solution states by Mössbauer spectroscopy and in the frozen-solution state by EPR spectroscopy.\textsuperscript{[21]} The potentials are 0.38 and 0.1 V vs Fc/Fc\textsuperscript{+} (0.40 V vs Fc/Fc\textsuperscript{+}).

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\text{H}_2\text{O}_2 + \text{Fe}^{\text{III}} = \text{H}_2\text{O} + \text{Fe}^{\text{II}}
\]

Addition of concentrated HCl to solutions of either the brown complex [[tpenaH]Fe(μ-O)Fe(tpenaH)]\textsuperscript{4+} (in water/EtOH) or of the red-orange complex [Fe(tpena)]\textsuperscript{2+} (in acetonitrile) resulted in immediate formation of [Fe(Cl)(tpenaH)]\textsuperscript{2+}, as manifested by a colour change to yellow, \(\lambda_{\text{max}} = 312\) and 361 nm (Eqs. (1 a) and (1 b), respectively).

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\begin{align*}
\text{[}[\text{tpenaH}]\text{Fe}(\mu-\text{O})\text{Fe}[\text{tpenaH}]^{4+} + 2\text{HCl} &\rightarrow 2 \text{[Fe(tpena)]}^{2+} + \text{H}_2\text{O} \quad \text{(1a)} \\
\text{fac/mer-}[\text{Fe}(\text{tpena})]^{2+} + \text{HX} &\rightarrow \text{FeX(tpena)}^{2+} \quad \text{X} = \text{Cl}^{-}, \text{OOH}^{-} \quad \text{(1b)}
\end{align*}
\]

Reaction of HCl and H\textsubscript{2}O\textsubscript{2} with [Fe(tpena)]\textsuperscript{2+} to form [FeX(tpenaH)]\textsuperscript{2+} (X = Cl\textsuperscript{-}, OOH\textsuperscript{-})

The single-crystal X-ray structure of [Fe( Cl)(tpenaH)]\textsuperscript{2+} ([ClO\textsubscript{4}]\textsubscript{2-}EtOH\textsubscript{2}H\textsubscript{2}O (Figure 2a) shows that the iron(III) ion is pentacoordinated by tpenaH, with a chlorido ligand occupying the sixth site. The pyridine arm attached to the same amine group, as the glycyl arm does not coordinate to the iron(III)
Addition of $\text{H}_2\text{O}_2$ to $[\text{Fe}(\text{tpena})]^{2+}$ in acetonitrile resulted in an immediate colour change from red to purple, indicative of the formation of an Fe(III)-hydroperoxido adduct structurally analogous to the HCl adduct, namely $[\text{Fe}^\text{III}(\text{OOH})(\text{tpena})]^{2+}$ [Eq. (1b)]. The concentration of the transient peroxido complex in acetonitrile is maximized under conditions that minimize the concentration of the hemihydrate, $[(\text{tpena})\text{Fe}(-\text{O})\text{Fe}(-\text{tpena})]^{2+}$, supporting the view that the anhydrate $[\text{Fe}(\text{tpena})]^{2+}$ is the immediate precursor for reaction with $\text{H}_2\text{O}_2$.

Purple solutions of $[\text{Fe}^\text{II}(\text{OOH})(\text{tpena})]^{2+}$ in acetonitrile, decay over 30 s at room temperature and over several hours at $-40^\circ\text{C}$. The rate of decay for $[\text{Fe}^\text{II}(\text{OOH})(\text{tpena})]^{2+}$ is significantly faster than that for $[\text{Fe}^\text{III}(\text{OOH})(\text{metpen})]^{2+}$ generated in methanol from $[\text{Fe}(\text{metpen})\text{Cl}](\text{PF}_6)$ with 50 equiv of $\text{H}_2\text{O}_2$ at room temperature. Of relevance to the oxidizing ability of $[\text{Fe}^\text{II}(\text{OOH})(\text{tpena})]^{2+}$ (see below) is that it cannot be observed in methanol; this is in stark contrast to the $[\text{Fe}^\text{II}(\text{OOH})(\text{Rtpen})]^{2+}$ complexes, for which methanol is the favoured solvent for generation.

### Spectroscopic properties of $[\text{Fe}(\text{OOH})(\text{tpena})]^{2+}$

The transient purple species, assigned as $[\text{Fe}^\text{II}(\text{OOH})(\text{tpena})]^{2+}$, shows an absorption band at 520 nm ($\varepsilon = 465 \text{M}^{-1}\text{cm}^{-1}$), consistent with an Fe(III) $\rightarrow$ ROO$^-$ charge-transfer transition (Figure 3a, red curve). The Raman spectrum elicited at $\lambda_{\text{exc}} = 532 \text{ nm}$ shows resonantly enhanced bands at 613 and 788 cm$^{-1}$ (Figure 3b), which can be assigned to Fe-O and O-O stretching modes, respectively, by comparison with previous literature; see Table 1. The EPR spectrum of a frozen solution shows a rhombic signal ($g = 2.21, 2.15, 1.96$; Figure 3c). The frozen-solution-state Mössbauer spectrum displays a doublet with $\delta = 0.21 \text{ mm s}^{-1}$ and $\Delta E_Q = 2.08 \text{ mm s}^{-1}$ (14%, Figure 3d), which is consistent with a low-spin Fe(III) species. The spectrum also shows the presence of the EPR-silent starting complex $[(\text{tpena})\text{Fe-O-Fe}(\text{tpena})]^{+}$ with $\delta = 0.43 \text{ mm s}^{-1}$, $\Delta E_Q = 1.63 \text{ mm s}^{-1}$ (14%)[21]. The structure of $[\text{Fe}^\text{II}(\text{OOH})(\text{tpena})]^{2+}$ can be any of six diastereoisomers (Scheme 4). However, the simplicity of the Raman, Mössbauer, and EPR spectra implies that one of these isomers dominates, notwithstanding the possibility that the differences between the stereoisomers are insufficient to cause significant changes in the vibrational, nuclear, and spin characteristics. In the present study, the precise stereochemistry of the intermediate is not of specific concern and for simplicity of the data analyses, it is assumed that a single diastereoisomer of $[\text{Fe}^\text{II}(\text{OOH})(\text{tpena})]^{2+}$ is formed, cor-

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**Scheme 4.** Possible diastereoisomers of $[\text{Fe}(X)(\text{tpena})]^{2+}$: $X = \text{Cl}^-$, $\text{OH}^-$, $\text{OOH}^-$.
responding to that observed in the crystal structure of the HCl adduct, Figure 2 (i.e., A in Scheme 4).

**Deprotonation of [Fe(OOH)(tpenaH)]^{2+}**

The addition of NEt₃ (30 equiv) to solutions of [Fe(III)(OOH)(tpenaH)]^{2+} and excess H₂O₂ in acetonitrile results in an instant colour change from purple to blue and the appearance of a new absorption band at 675 nm (Figure 3, blue line). The lifetime of the new species is about 10 min at 0 °C when generated from 50 equiv of H₂O₂ and 30 equiv of Et₃N. Immediate loss of the Fe/C0 and O/C0 bands of the end-on Fe(III)-OOH in the Raman spectrum is accompanied by the appearance of the corresponding bands of a side-on peroxido complex at 473 and 815 cm⁻¹ (Figure 3, b), consistent with assignment of the species as [Fe(III)(OO)(tpenaH)]^{+}. The band positions are close to those reported for [Fe(III)(OO)(tpen)]^{+} and [Fe(III)(OO)(metpen)]^{+} (Table 1). A high-spin signal (gₑff = 8.8, 5.0, 4.3, 4.2, 3.5) appears in the EPR spectrum (Figure 4, a). The Mössbauer spectrum (Figure 4, b) of a sample composed of ⁵₇Fe-labelled [Fe(III)(OO)(tpenaH)]^{2+} (microwave frequency 9.31542 GHz, 110 K, [Fe] = 2 mM, fit in grey). The spectrum shows the presence of a significant amount of the EPR-silent starting material ([tpenaH]Fe-O-Fe(tpenaH)]^{4+} (d = 0.46 mm s⁻¹, ΔE₀ = 1.68 mm s⁻¹, 53 %). It is interesting to note that this spectrum does not show the presence of unidentified iron complexes derived from the decomposition of tpna (see below) in contrast to the spectrum for [Fe(III)(OOH)(tpenaH)]^{2+} (Figure 3, d). This lack of decomposition might suggest that the peroxide species is less reactive than the hydroperoxide species. This idea is supported by the fact that in order to acquire this clean spectrum it was necessary to add the base before the H₂O₂.

![Figure 3. Solution-state spectroscopic characterization of [Fe(III)(OOH)(tpenaH)]^{2+} and [Fe(III)(OO)(tpenaH)]^{+}.](image)

![Figure 4. Frozen-solution-state spectroscopic characterization of [Fe(III)(OOH)(tpenaH)]^{2+} and [Fe(III)(OO)(tpenaH)]^{+}.](image)

followed by rapid freezing in liquid N₂. This protocol meant that the presumably more labile [Fe(OOH)(tpena)]²⁺ did not get the chance to form in any significant concentration.

Spectroscopic data for [Fe(tpena)]²⁺ peroxide adducts are consistent with a side-on bound peroxide FeIII complex in [FeIII(OO)(tpenaH)]⁻ by comparison with iron complexes of Rtpen (Table 1, R = Me, BzCH₂, PyCH₂). This species is potentially intramolecularly (Scheme 5) or intermolecularly H-bonded, with the solid-state structure of [Cr(OH)(tpenaH)]⁻ furnishing a structural analogue for the latter. The pendant pyridinium moiety of the tpena ligand is a second site available for deprotonation by a base, and [Fe(OO)(tpena)] is a plausible product from the reaction of [FeIII(OOH)(tpenaH)]²⁺ with two equivalents of base (Scheme 5). However, in this situation, the pyridine is expected to re-coordinate to the iron atom to form a seven-/eight-coordinated product for η⁷- and η⁸-O₂⁻, respectively. This is not expected to be sterically too demanding, because the N-Fe-N angles for multidentate ligands with ethylenediamine backbones are generally less than 90°, thereby providing a relatively open face on the opposite side of the metal ion. Indeed, heptacoordination has been structurally characterized in the high-spin d⁶ metal ion complexes [Fe(OIPh)(tpena)](ClO₄)₂ [20] and [Mn(OH₂)(tpena)](ClO₄)₂ [21]. The relatively open face presented by tpena in these structures suggests that formation of a heteroleptic complex with an η⁷-diatomic ligand is also a reasonable structure for the peroxido complex, especially since η⁷-O₂⁻ ligands are no more sterically demanding than monodentate oxide (O₂⁻) ligands. Addition of further base leads to the formation of yellow solutions, with vigorous decomposition of H₂O₂ and ultimately decomposition of further base leads to the formation of yellow solutions, thereby furnishing a structural analogue for the latter.

The relatively open face presented by tpena in these structures suggests that formation of a heteroleptic complex with an η⁷-diatomic ligand is also a reasonable structure for the peroxido complex, especially since η⁷-O₂⁻ ligands are no more sterically demanding than monodentate oxide (O₂⁻) ligands. Addition of further base leads to the formation of yellow solutions, with vigorous decomposition of H₂O₂ and ultimately decomposition of the complex (see below), such that the precise details of the protonation state cannot be readily determined experimentally.

Consideration of Table 1 shows that the most significant spectroscopic difference is that the Fe³⁺ — OOH⁻ and Fe³⁺ — OO⁻ LMCT bands for the end-on hydroperoxido and side-on peroxido Fe³⁺-tpena complexes are at shorter wavelengths than those for the analogous Rtpen-based complexes. The
for [Fe(OOH)(tpenaH)]^{2+} is hypsochromically shifted by about 20 nm, and the \( \lambda_{\text{max}} \) for [Fe(\text{OO})(tpenaH)]^{+} is shifted by 60, 75, and 95 nm compared to those reported for [Fe(\text{OO})(tpena)]^{+}, [Fe(\text{OO})(metpen)]^{+}, and [Fe(\text{OO})(btztpen)]^{+}, respectively. The larger difference for the peroxido complexes may be related to the intramolecular H-bonding.

**Competition between H$_2$O$_2$ disproportionation and ligand decomposition**

A large excess (20–50 equiv with respect to iron) of H$_2$O$_2$ is required to generate maximum steady-state concentrations of [Fe(\text{OOH})(tpenaH)]^{2+} and [Fe(\text{OO})(tpenaH)]^{+}, under which conditions evolution of gas is observed. Analysis of the dissolved and evolved volatiles by means of membrane inlet mass spectrometry (MIMS) and head-space Raman spectroscopy (HS-RS; \( \lambda_{\text{exc}} = 322 \text{ nm} \)) confirmed that the gas evolved was predominantly O$_2$. Addition of $^{18}$O-labelled water in a 1:1:1 ratio of H$_2$O$_2$:H$_2$O:O$_2$ mixture, confirmed that the O$_2$ evolved did not contain $^{18}$O and hence that the two oxygen atoms in the evolved O$_2$ were derived from H$_2$O$_2$. Thus, [Fe(\text{tpena})]^{3+} catalyses H$_2$O$_2$ disproportionation rather than a more demanding oxidation of water.$^{[26]}$ To the best of our knowledge, H$_2$O$_2$ disproportionation catalysed by exclusively N-donor supported iron(III) peroxides (Scheme 2 a; \( R=\text{CH}_2\text{PyCH}_3 \)) has not been reported.$^{[10,11,17,29]}$ Since it seemed plausible that this reaction had simply been overlooked (because bubbles were not visible) in previous studies of the generation of non-heme Fe$^{III}$ peroxides, we checked for this possible reaction in the present study by applying MIMS to monitor the reactions of [Fe(\text{Cl})(\text{metpen})]$^{3+}$ and [Fe(\text{tpen})]$^{3+}$ with 50 equiv of H$_2$O$_2$. We can verify that O$_2$ evolution, and hence catalase activity, does not occur as a side reaction when these exclusively N-donor ligands support the peroxide complexes.

In further contrast to the exclusively N-donor-supported iron peroxide complexes, the hydroperoxo species, [Fe(\text{OOH})(\text{tpenaH})]$^{2+}$, is not regenerated by the addition of a second portion (50 equiv) of H$_2$O$_2$ after the cessation of O$_2$ evolution, nor does catalytic H$_2$O$_2$ disproportionation resume. These observations indicate that either the catalyst is decomposed by H$_2$O$_2$ when the concentration of H$_2$O$_2$ is sufficiently low for competing C–H oxidation of the tpena ligand to become kinetically competent, or the increase in water concentration (introduced with and formed from H$_2$O$_2$) drives the formation of a kinetically inert oxido-bridged species [(tpenaH)Fe(u-O)Fe(tpena)]$^{4+}$.$^{[24,30]}$ To determine which of these pathways is pertinent, two equivalents of H$_2$O$_2$ were added to solutions of [Fe(\text{tpena})]$^{2+}$ in acetonitrile. A colour change to purple was not observed. Head-space infrared spectroscopy (HS-IRS), however, showed that CO$_2$ was produced. The only carbon sources available for CO$_2$ production were the solvent acetonitrile and/or tpena. Monitoring both the O$_2$ and CO$_2$ releases by MIMS (Figure 5 a) following the addition of 50 equiv of H$_2$O$_2$ revealed that O$_2$ was predominantly released in the early stages of the reaction. Quantitative analysis of the CO$_2$ release by HS-IRS showed that approximately seven CO$_2$ molecules per iron centre (Figure 5 b) were produced. Increasing the amount of H$_2$O$_2$ added did not result in an increase in CO$_2$ formation, and it can therefore be concluded that the source of CO$_2$ was degradation of tpena rather than oxidation of acetonitrile. Specifically, the CO$_2$ must be derived from the aliphatic and carboxylate carbon atoms of tpena, as would be expected for aliphatic C–N oxidative cleavage/hydrolysis reactions.

The changes in iron speciation after the addition of 50 equiv of H$_2$O$_2$ were monitored by UV/Vis absorption, Raman, EPR, and Mössbauer spectroscopies. The band at 520 nm due to the purple [Fe(\text{OOH})(tpenaH)]$^{2+}$ chromophore decayed completely, and then a new and more intense band appeared at 469 nm (Figure 6 a). The absence of an isosbestic point suggests that the conversion between these iron-based chromophores involves relatively long-lived intermediates that do not absorb in the visible region. Time-resolved head-space FTIR and UV/Vis absorption data indicated that the growth of the band at 469 nm was concomitant with the release of CO$_2$ and the consequent growth of the absorbance at 2360 cm$^{-1}$ in the HS-IR spectra. A fit of an EPR spectrum recorded from a reac-
of aqueous H$_2$O$_2$ with [Fe(tpena)]$_2$$^+$, expected to be EPR silent. Bands at $\nu=634$, 1192, and 2094 cm$^{-1}$ appeared in the Raman spectrum ($\lambda_{exc}=532$ nm) of equivalently treated solutions (Figure 6c). The band at $\nu=2094$ cm$^{-1}$ is consistent with the presence of Fe$^4$-coordinated acetonitrile.$^{[31]}$ A $^1$H NMR spectrum of the reaction mixture in CD$_3$CN recorded after 16 h (and hence coinciding with the presence of the EPR-silent species with an absorption at 469 nm) showed the characteristic signal of NH$_3$ (three resonances of equal intensity centred at $\delta=6.61$ ppm, $J_{NNH}=52$ Hz; Supporting Information, Figure S2). This demonstrated that the production of NH$_3$ occurred concomitantly with the production of tpenan-derived CO$_2$. The signals remaining in the aromatic region (7–9 ppm) suggested that the pyridine groups remained intact. Positive- and negative-ion ESI-MS did not provide evidence for the formation of a complex with pyridine ligands that might be associated with the species at 469 nm. Indirectly, however, the ESI-MS data provide further evidence that all of the aliphatic C atoms of the ligands were converted into CO$_2$ through the absence, for example, of picolinato complexes that have previously been observed to form through the reaction of aminopyridyl-metal complexes with peroxides.$^{[32]}$ Overall, the data lead to the conclusion that reaction of [Fe(tpena)]$^{2+}$ with a large excess of H$_2$O$_2$ results primarily in H$_2$O$_2$ disproportionation, but is accompanied by concurrent oxidative decay of the tpena ligand, which occurs primarily when the concentration of H$_2$O$_2$ is low. A mixture of heteroleptic iron(II) complexes of pyridine, ammonia, and/or acetonitrile ligands is ultimately formed through the oxidative decomposition of [Fe$^4$(tpena)]$^{2+}$.

**Catalytic alcohol oxidation overrides catalase activity and ligand decomposition**

In stark contrast to the reactions of [Fe$^3$(Cl)(Rtpena)]$^+$/C$^0$ with excess H$_2$O$_2$ in methanol,$^{[10,11,17]}$ the addition of 50 equiv of H$_2$O$_2$ to solutions of [Fe$^4$(tpena)]$^{2+}$ in methanol does not give rise to detectable amounts of purple [Fe$^4$(OOH)(tpenaH)]$^{2-}$.$^{[34]}$ This is because methanol is oxidized. Analysis using the Hantsche reaction$^{[33]}$ and UV/Vis absorption spectroscopy showed that formaldehyde was produced in approximately 35% yield based on the initial H$_2$O$_2$ concentration. Thus, the activation of H$_2$O$_2$ by [Fe$^4$(tpena)]$^{2+}$ can be directed to perform substrate oxidation. This observation inspired us to examine a more readily oxidizable substrate, benzyl alcohol, in acetonitrile (bond dissociation energies for H–CH$_2$OH and H–CH(OH)Ph are 96 and 79 kcal mol$^{-1}$, respectively$^{[35,36]}$). The addition of 50 equiv of H$_2$O$_2$ to [Fe(tpena)]$^{2+}$ in the presence of 500 equiv of benzyl alcohol did not result in either O$_2$ or CO$_2$ evolution, and hence...
neither $\text{H}_2\text{O}_2$ disproportionation nor tpena decomposition occurred. In contrast to the reactions performed in methanol, under these conditions, $\left[\text{Fe}^{IV}(\text{O})(\text{tpenaH})\right]^{2+}$ was observed spectroscopically due to the lower concentration of the alcohol substrate. The addition of a second portion of $\text{H}_2\text{O}_2$ (50 equiv) resulted in reappearance of the absorption band of $\left[\text{Fe}^{III}(\text{OOH})(\text{tpenaH})\right]^{2+}$ with the same intensity as after the first addition (Figure 7). Continued batchwise addition of $\text{H}_2\text{O}_2$ eventually led to decomposition of the ligand, that is, the band at 469 nm intensified and the purple colour, due to the presence of $\left[\text{Fe}^{III}(\text{OOH})(\text{tpenaH})\right]^{2+}$, was lost. Thus, tpenaH oxidation competes with alcohol oxidation and the presence of a large excess of alcohol, or its use as the solvent delays the onset of ligand oxidation. $^1\text{H}$ NMR spectroscopic analysis showed, after five additions of 50 equiv of $\text{H}_2\text{O}_2$ over 10 min, 50% conversion of benzyl alcohol to benzaldehyde and hence near-stoichiometric conversion with respect to the oxidant. A control reaction in the absence of $\left[\text{Fe}(\text{tpena})\right]^{2+}$ showed that, under otherwise identical conditions, benzyl alcohol was oxidized by $\text{H}_2\text{O}_2$ with only 32% conversion after 20 h.[23]

Mechanistic considerations

The reaction of $\left[\left(\text{tpenaH}\right)\text{Fe-O-Fet(tpenaH)}\right]^{+}$ with $\text{Ce}^{IV}$ in water produces the iron(IV) oxo complex, $\left[\text{Fe}^{IV}(\text{O})(\text{tpenaH})\right]^{2+}$, and recently we have generated this same species electrochemically, also in water.[24] In both of these studies, we demonstrated $\left[\text{Fe}^{IV}(\text{O})(\text{tpenaH})\right]^{2+}$ to be a promiscuous oxidant in the absence of hydroxyl radicals. It attacks a broad range of C–H bonds by hydrogen-atom transfer. Thus, $\left[\text{Fe}^{IV}(\text{O})(\text{tpenaH})\right]^{2+}$ displays radical character. Calculations by Faponle et al. show that $\left[\text{Fe}^{IV}=(\text{O})(\text{metpen})\right]^{2+}$ can be generated by homolytic cleavage of $\left[\text{Fe}^{IV}\left(\text{OOH}\right)(\text{metpen})\right]^{2+}$, and it is the Fe$^{IV}$ oxo species that reacts with substrates.[24] This reaction has been demonstrated in the gas phase.[25] However, the phase of the reaction medium (and second coordination sphere) is likely to tune the O–O bond cleavage reaction. With these facts in mind, we propose that the $\text{H}_2\text{O}_2$ activation and reactivity described in the present study can be rationalized in terms of homolytic O–O bond cleavage of the hydroperoxide ligand in $\left[\text{Fe}^{III}(\text{OOH})(\text{tpenaH})\right]^{2+}$. This reactivity is in contrast to the behaviour of Fe$^{III}$-OOH based on neutral N5 donor systems. In fact, peroxide dissociation[17,20] is a highly competitive pathway for the decomposition of (NS)Fe$^{III}$-OOH species. It can thus be concluded that for the iron-tpena system, homolytic O–O bond cleavage occurs in $\left[\text{Fe}^{IV}(\text{OOH})(\text{tpenaH})\right]^{2+}$, resulting in the formation of $\left[\text{Fe}^{IV}(\text{O})(\text{tpenaH})\right]^{2+}$ and a hydroxyl radical. Both are aggressive hydrogen-atom abstractors and will react with methanol, benzyl alcohol, and hydrogen peroxide to form the methanoyl, benzoyl, and hydroperoxide ($\text{CH}_2\text{OH}, \text{C}_6\text{H}_5\text{CHOH}, \text{OOH}$) radicals, respectively. In turn, these radicals will propagate chain reactions and radical terminations to give the detected products, $\text{CH}_3\text{O}, \text{C}_6\text{H}_5\text{CHO},$ and $\text{O}_2$. Interconnected catalytic cycles for $\text{H}_2\text{O}_2$ disproportionation and alcohol oxidation are proposed in Scheme 6.

Perspective on the tunability by varying the supporting ligand in $\text{H}_2\text{O}_2$ activation by non-heme iron complexes

Compared to analogous iron(III)-hydroperoxide complexes based on supporting N5 and N6 ligands containing exclusively pyridine and tertiary amine donors (Scheme 2 a) and analogous $\text{N,N}$-bis(2-pyridylmethyl)-$\text{N}$-bis(2-pyridyl)methylamine[32] (N4py) systems, the influence of a biomimetic carboxylato donor is demonstrated by the significant difference in Fe$^{IV}$/Fe$^{III}$ redox potentials of the parent $\left[\text{Fe}(\text{tpen})\right]^{3+}$ and $\left[\text{Fe}(\text{tpena})\right]^{2+}$ complexes. The latter is shifted to lower values by an average of 360 mV for the diastereoisomers in acetonitrile. A practical consequence of the lower redox potential is that tpena-Fe$^{IV}$ complexes are isolated, and these are redox-stable in the +3 oxidation state in all solvents examined.[20,21] This result stands in contrast to observations for the complexes of tpen and related N5 neutral pentadentate ligands (Scheme 2 a), for which the iron(III) complexes are those most readily isolated, especially in solvents such as acetonitrile. These are thermodynamic sinks,

[Figure 7. Time dependence of the absorbance at 520 nm in the presence of 500 equiv of PhCH$_2$OH ([Fe] = 0.5 mM). The batchwise addition of 50 equiv of $\text{H}_2\text{O}_2$ causes jumps in the absorbance due to formation of the Fe$^{IV}$-OOH intermediate.]

[Scheme 6. Connected catalytic cycles for $\text{H}_2\text{O}_2$ disproportionation and $\text{O}_2$ evolution, as well as methanol (R = H) and benzyl alcohol (R = C$_6$H$_5$) oxidation by $\text{H}_2\text{O}_2$.]
retarding their reactivity with H₂O₂. This tendency towards greater stability in higher iron oxidation states will have a significant impact on the chemistry of the iron-tpena complexes and hence on the construction of proposed catalytic cycles. The pro-catalyst and resting state is iron(III) and not iron(II). As such, the process of peroxide adduct formation does not require a prior oxidation step from iron(II) to iron(III). The Fe⁴⁺/Fe⁵⁺ couple can be reasonably expected to follow this trend towards lower potentials, and this will favour promotion of the homolytic cleavage of the FeO-OH bond in the hydroperoxide adduct to readily attain an iron(IV) oxo species. This is manifested in significantly shorter lifetimes for [Fe(OOH)(tpenaH)]²⁺ and [Fe(OO)(tpenaH)]⁺ compared to the corresponding systems based on N5/N6 Rtpen ligands. A further contrast to the N5/N6 donor-supported systems for the reaction of H₂O₂ with the resting state iron(III) in [Fe(tpena)]²⁺ is that no deprotonation of the H₂O₂ is needed. It is an addition reaction accompanied by charge separation due to concomitant pyridine decoordination and pyrimidine formation. The ligand is converted from monoanionic hexadentate (tpena) to zwitterionic pentadentate (tpenaH). With one carboxylato donor and a second base in the coordination sphere, [Fe(OOH)(tpenaH)]²⁺ and its conjugate base [Fe(OO)(tpenaH)]⁻ are particularly germane biomimics for non-heme iron(III) peroxides. The peroxide activation chemistry that we have observed is pertinent to elucidating mechanisms for O₂-activating enzymes in which Gly/Asp groups are coordinated to the O₂-binding site on iron. In particular, we note that the non-heme 1 Asp/3 His-coordinated iron superoxide dismutase evolves O₂ in a similar manner to the Fe-tpena system studied here (although the disproportionated substrate is O₂⁻ and not H₂O₂). The basic amino acid residues found in the second coordination sphere of non-heme active sites are proposed to facilitate proton-coupled redox reactions, and a similar role for the dangling pyridine/pyrimidine groups of the tpena system is feasible. The contrast in peroxide activation reactivity between [Fe(tpena)]²⁺ and the parent pentadentate N4O Rbpena-based Fe⁴⁺ systems (Scheme 2b) described in the Introduction is also worth noting: ligand oxygenations result from reactions of the iron(III) starting complexes with H₂O₂ without the detection of intermediate peroxide adducts (Scheme 2b). The two types of O atom insertions observed are consistent with heterolytic O–O cleavage of a putative (Rbpena)Fe⁴⁺O–O(H) intermediate to form a putative Fe⁷⁺ oxo species. This reactive species can then transfer [O] to the aromatic C–H or N in bzbpna and mebpna, respectively. The iron(III) complexes of the modified “RbpenaO” ligands may be unable to activate H₂O₂, and are therewith stable towards oxidative decomposition, in contrast to the iron complex of tpena. Interestingly, the manganese complexes of Rbpena and tpena can withstand thousands of equivalents of organic peroxides without decomposition or ligand modification.

Conclusions

Methanol oxidation to formaldehyde and stoichiometric yields of benzaldehyde from the [Fe(tpena)]²⁺-catalysed oxidation of benzyl alcohol by H₂O₂ have been realized in the present study. In the absence of a large excess of a second substrate, H₂O₂ disproportionation is catalysed by [Fe(tpena)]²⁺ through a related mechanism. However, in the absence of other oxidizable substrates (methanol, benzyl alcohol, and H₂O₂), oxidative decay of [Fe(tpena)]²⁺ occurs through the spectroscopically detectable intermediate [Fe(OOH)(tpenaH)]²⁺. Release of all of the aliphatic carbon atoms and amine groups as CO₂ and NH₃, respectively, has been demonstrated. The reactivity patterns observed (catalysis of the oxidation of alcohols, catalase activity, and tpena degradation, Scheme 3) reflect the higher C–H bond strength in MeCN compared to MeOH, the aliphatic C–H bonds in tpena, and the O–H bond in H₂O₂, respectively. Overall, the H₂O₂ activation chemistry described here stands in contrast to that reported previously for the pentadentate N5 supporting ligands [Fe⁴⁺(OOH)(Rtpen)]²⁻ and [Fe⁴⁺(OOH)(N4py)]²⁻ and a carboxylate-containing N4O pentadentate supporting ligand [Fe⁴⁺(OOH)(Rbpena)]²⁻. We have shown: 1) facile homolytic Fe⁴⁺–OH cleavage in solution to produce two aggressive H-atom abstractors, Fe⁴⁺=O and H₂O₂; 2) catalytic H₂O₂ disproportionation, 3) catalytic alcohol oxidation with stoichiometric yields, and 4) total destruction of the aliphatic part of tpena in the presence of low concentrations of H₂O₂. By tuning the penta- and hexadentate ethylenediamine-backboned ligands (Scheme 2), a tendency towards the limiting reaction types depicted in Equations (2), (3), and (4) for Fe⁴⁺-peroxide adducts has been exposed. It seems that H₂O₂ activation is more effective for the carboxylato ligands and the difference in reactivity seen for the N4O (Rbpena) and N5O (tpena) ligand systems must be due to the availability of a second base in the coordination sphere for the latter. The proximity of this group suggests that it may participate at many stages, from its decoordination to allow adduct formation by charge-separated H₂O₂ addition to H-bonding in the peroxide intermediates. In turn, this electronic modulation may effect a homolytic O–O cleavage rather than the heterolytic cleavage and intramolecular oxygenation that occurs with the otherwise stereochemically and electronically similar N4O Rbpena as a supporting ligand.

Dissociation:

\[ \text{Fe}^{III}\text{(OOH)}(\text{Rtpen})^{2+} + \text{HX} \rightarrow [\text{Fe}^{IV}\text{(X)}(\text{Rtpen})]^{2+} + \text{HOOH} \quad (2) \]

O–O heterolysis:

\[ \text{Fe}^{IV}\text{(OOH)}(\text{Rbpena})^{2+} \rightarrow [\text{Fe}^{IV}(\text{RbpenaO})]^{2+} + \text{OH}^{-} \quad (3) \]

O–O homolysis:

\[ \text{Fe}^{IV}\text{(OOH)}(\text{tpenaH})^{2+} \rightarrow [\text{Fe}^{IV}(\text{O})(\text{tpenaH})]^{2+} + \text{OH}^{-} \quad (4) \]

Our work not only presents a germane mimic for non-heme iron chemistry, especially in terms of the carboxylato group and the second coordination sphere base, but also adds to our knowledge of the ligand design features important for activating H₂O₂, demonstrates controllable bifurcation in catalysed external substrate oxidation reactions, and indicates that destruct-
tive oxidation of the supporting ligand can be avoided through appropriate experimental design [Eqs. (2–4)].

Experimental Section

Materials and preparations

N,N,N-Tris-(2-pyridylmethyl)ethylenediamine-N'-acetic acid (tpenaH), [tpenaH]Fe-O-Fe(tpenaH)ClO4·(H2O), [FeCl]tpen[PF6], [FeCl]tpen[penta]ClO4 and Fe(tpena)ClO4 were prepared as described previously. [1]O2H2O was supplied by Rotem Industries Ltd. and all other chemicals were purchased from Sigma-Aldrich.

CAUTION!!! Perchlorate salts of metal complexes are potentially explosive and should be handled with caution in small quantities.

[Fe(OH)][tpenaH]2+ and [Fe(OOH)(tpena)H]+: ([tpenaH]Fe-O-Fe(tpenaH))ClO4·(H2O) was dissolved in acetonitrile and the solution was allowed to stand for 10 min until ([tpenaH]Fe-O-Fe(tpenaH))2+ had dehydrated to [Fe(tpena)]2+. This solution was then treated with 50 equiv of H2O2 (50% in water, w/w) to give [Fe(OOH)(tpena)H]+ and [Fe(OOH)(tpena)H]2+ by formation of the subsequent addition of 30 equiv of Et3N.

[FeCl(tpena)][ClO4]2·(EtOH)-2(H2O): [FeCl(tpena)]2·(H2O) (773 mg, 1.7 mmol) was added to tpenaH (655 mg, 1.7 mmol) in acetonitrile (5 mL), water (5 mL), and ethanol (5 mL), and the mixture was adjusted to pH 3 with HCl(aq). Upon slow evaporation of the volatiles, yellow crystals of [FeCl(tpena)][ClO4]2·(EtOH)-2(H2O) (702 mg, 54%) were deposited after two weeks. ESI-MS (MeCN): m/z: 479.1 ([FeCl(tpena)-2H]+, 78%), 481.1 ([FeCl(tpena)+], 81%), 482.1 ([FeCl(tpena)+], 100%), ESI-MS (H2O): m/z: 446.1 ([Fe(tpena)+], 34%), 454.1 ([Fe(tpena)Fe-O-EtOH][tpena]+), 100%), 463.1 ([Fe(OH)-tpena]+, 85%); IR (KBr): v: = 1610 (C=O), s, 1098 cm⁻¹ (ClO4+, νs); elemental analysis calc (%) for C148H10N6O6Cl4Fe (FeCl(tpena)[H]-ClO4·2H2O: C 36.82, H 4.07, N 9.76; found: C 36.21, H 3.65, N 9.27.

Instrumentation and methods

UV/Vis spectra were recorded from solutions in 1 cm quartz cuvettes on either an Agilent 8453 spectrophotometer with a UNISOKU CoolSpek UV USP-203 temperature controller or an Analytik Jena Specord S600 with a Quantum Northwest TC 125 temperature controller. Raman spectra were recorded from samples in 1 cm quartz cuvettes at either 532 nm (300 mW at source, Cobalt Lasers) as described previously or 691 nm (75 mW at source, Ondax Lasers). The solutions were cooled with a Quantum Northwest TC 125 temperature controller and the spectra were obtained at −30°C. Data were recorded and processed using Solis (Andor Technology) with spectral calibration with respect to the Raman spectrum of MeCN/toluene (50:50, w/w). Baseline correction was performed for all spectra and normalized to the solvent band at 750 cm⁻¹. EPR spectra (X-band) were recorded on a Bruker EMX Plus CW spectrometer (mod. amp.: 10 G, attenuation: 10 dB) on frozen solutions at 110 K. In order to follow the decay of the iron species, the samples for measurements (200 μL) were transferred to EPR tubes and frozen in liquid nitrogen at different times. The software packages eview4w and esimX were used for simulations. 1H NMR (400.12 MHz) spectra were recorded on a Bruker Avance III 400 spectrometer at ambient temperature. Chemical shifts are denoted relative to the residual solvent peak (CD3CN, 1.94 ppm). Mössbauer spectra were obtained with conventional constant acceleration spectrometers with sources of 57Co in rhodium foil. The spectra were collected at 14 K. Isomer shifts are given relative to that of α-Fe at 295 K. Infrared spectra (IR) were obtained on a Hitachi 270-30 IR spectrometer from samples in KBr pellets. Head-space FTIR spectra were recorded from samples in sealed 1 cm quartz cuvettes on a JASCO FT-NIR/MIR-4600 spectrometer with a resolution of 8 cm⁻¹. The concentration of CO2 released was quantified on the basis of standard solutions of Na2CO3 in water with addition of 3 equiv acid (HCl) to force the release of CO2. Aliquots (1 mL) of the solution were placed in a sealed cuvette, and the head-space was monitored before and after the addition of acid. A standard curve based on the absorbance at 2360 cm⁻¹ was fitted to [CO2] < 5 mm: Abs (2360 cm⁻¹) = 0.0300 mm⁻¹ [CO2] + 0.0084 and [CO2] > 5 mm: Abs (2360 cm⁻¹) = 0.0281 mm⁻¹ [CO2] + 0.0213. MIMS spectra were recorded using a Prisma quadrupole mass spectrometer (Pfeiffer Vacuum, Asllar, Germany). A flat sheet membrane (250 μm) of polymethyl siloxane (Sil-Tec sheeting, Technical Products, Decatur, GA, USA) separated the vacuum chamber (1 x 10⁻¹ mbar) from the solution in the sample chamber (total volume 2.5 mL), which was stirred mechanically. The data were recorded and processed using Quadstar 422 (Pfeiffer Vacuum, Asllar, Germany). The reaction chamber was filled with a solution of [Fe(tpena)]2+, and H2O2 was injected directly into the solution in the sample chamber as the resulting gas evolution was simultaneously measured. Electrospray ionization (ESI) mass spectra were recorded in high-resolution positive-ion mode on a Bruker microTOF-QII mass spectrometer. Single-crystal X-ray diffraction data were collected on a Rigaku R-AXIS Iic image-plate system (MoKα, radiation) at 100 K. Cyclic voltammetry was performed on an Eco Chemie Autolab PGSTAT10 potentiostat/galanostat using a standard three-electrode setup with a Pt disc as the working electrode, a Ag/AgNO3 in 0.1 M TBAClO4 in MeCN as the reference electrode (0.01 m AgNO3 in 0.1 M TBAClO4 in MeCN; TBA: tert-butylammonium). The electrolyte was also 0.1 M TBAClO4 in MeCN. The working electrode was cleaned by polishing with 0.05 μm alumina followed by sonication, and the solutions were purged with nitrogen prior to measurements. The oxidation potential of Fc/Fc⁺ against Ag/Ag⁺ was measured as 0.08 V, and all oxidation potentials were converted accordingly.

CCDC 1559278 ([FeCl(tpena)][ClO4]2·(EtOH)-2(H2O)) contains the supplementary crystallographic data for this paper. These data are provided free of charge by The Cambridge Crystallographic Data Centre.

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Conflict of interest

The authors declare no conflict of interest.

Keywords: H2O2 activation · high-valent iron · hydroxyl radical · iron(IV) · N2O ligands · peroxides

Peroxide activation at Fe: A transient Fe\textsuperscript{III}-hydroperoxide intermediate has been spectroscopically identified during [Fe\textsuperscript{III}(tpena)]\textsuperscript{2+}-catalysed H\textsubscript{2}O\textsubscript{2} disproportionation in acetonitrile (see graphic). If benzyl alcohol is present, or methanol is used as solvent, H\textsubscript{2}O\textsubscript{2} disproportionation is inhibited in favour of high-yielding alcohol oxidation to the corresponding aldehyde. In the absence of excess substrate (alcohol or H\textsubscript{2}O\textsubscript{2}), tpena is oxidatively degraded.

*Coordination Chemistry*

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Directing a Non-Heme Iron(III)-Hydroperoxide Species on a Trifurcated Reactivity Pathway