Chapter 7 – Paper V

Catalytic Alkyl Hydroperoxide and Acylperoxide Disproportionation by a Nonheme Iron Complex

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The supporting information is found in the end of the chapter.
Chapter 7

Abstract

Alkyl hydroperoxides are commonly used as terminal oxidants because they are generally acknowledged to be stable towards disproportionation compared with \( \text{H}_2\text{O}_2 \). We show that alkylperoxide disproportionation is effectively catalyzed by \([\text{Fe(tpena)}]^{2+} \) (tpena = \( N,N,N'\)-tris(2-pyridylmethyl)ethylenediamine-\( N'\)-acetate). A peroxidase type mechanism, in other words, involvement of iron(IV)oxo species, is consistent with the rates and product distribution. Accordingly, \( \text{O}_2 \) and tert-butanol and cumyl alcohol are concurrently produced for substrates tert-butyl hydroperoxide and cumene hydroperoxide respectively, in the presence of \([\text{Fe(tpena)}]^{2+} \) with \( \text{O}_2 \) yields of 88 % and 44 % respectively. Rate constants for initial \( \text{O}_2 \) production ([Fe] 0.005 mol%) were measured to 3.66(6) mMs\(^{-1}\) and 0.29(3) mMs\(^{-1}\), respectively. Participating in the mechanism are spectroscopically detectable (UV/vis, EPR, resonance Raman) transient alkyl- and acyl-peroxide adducts, \([\text{Fe}^{III}\text{OOR(tpenaH)}]^{2+} \) (\( R = \text{C(CH}_3)_3 \), \( \text{C(CH}_3)_2\text{Ph} \), \( \text{C(O)PhCl} \); \( T_1/2 = 30\text{s} (5 \, ^\circ\text{C}), 20\text{s} (5 \, ^\circ\text{C}), 1\text{s} (-30 \, ^\circ\text{C}) \)) with their common decay product \([\text{Fe}^{IV}\text{O(tpenaH)}]^{2+} \). Concurrently organic radicals proposed to be ROO• were detected by EPR spectroscopy. A lower yield of \( \text{O}_2 \) at 23 % with an initial rate of 0.10(3) mMs\(^{-1}\) for the disproportionation of \( m\)-chloroperoxybenzoic acid is readily explained by catalyst inhibition by coordination of the product \( m\)-chlorobenzoic acid. Oxidative decomposition of the alkyl groups by a unimolecular \( \beta\)-scission pathway, favoured for cumene hydroperoxide, competes with ROOH disproportionation. Despite the fact that the catalytic disproportionation is effective, external C-H substrates - when they are present in excess of ROOH - can be targeted and catalytically and selectively oxidized by ROOH using \([\text{Fe(tpena)}]^{2+} \) as the catalyst.

Introduction

The most common motif for the active sites of non-heme iron \( \text{O}_2 \) activating enzymes is a single endogenous Asp or Glu donor accompanied by 1-3 His and exchangeable water molecules.\(^1\)\(^-\)\(^2\) It can be reasonably expected that the anionic carboxylato co-ligand will tune physical properties, not least redox potentials, with consequences for the activation of coordinated terminal oxidants. Biology provides examples: The shift from reversible \( \text{O}_2 \) binding in hemerythin to \( \text{O}_2 \) activation and catalysis of oxidation reactions by the related enzymes methane monooxygenase and ribonucleotide reductase.\(^4\) The same effects are observed by tuning of the axial endogeneous amino acid donor for heme systems.\(^3\) Despite these biological precedents, reports of biomimetic terminal oxidant activation using iron complexes of multidentate ligands containing a carboxylato donor remain relatively few by comparison to the considerable volume of work over the last three decades for iron complexes based on neutral aminopyridyl N-donor only ligands.\(^4\)\(^-\)\(^6\) Our efforts to fill this gap, have revealed that iron complexes of glycycl substituted tetra, penta and hexadentate aminopyridyl ligands activate a range of oxidants including \( \text{O}_2 \),\(^7\) \( \text{H}_2\text{O}_2 \),\(^7\)\(^-\)\(^8\) \( \text{PhIO} \),\(^9\)\(^,\)\(^10\) and methyl-morpholine-\( N\)-oxide\(^9\) with reactivity patterns that are distinct from those found for counterpart iron complexes based on neutral N4, NS and N6-donor only ligands. In addition, for these systems, water can be primed to act as the O atom donor for the production of oxidizing iron(IV)oxo complexes by electrochemical\(^11\) or Ce(IV)\(^12\) activation in aqueous solutions. Water is ultimately also the terminal source for the O atom of an iron(IV)oxo complex of a monocarboxylato chelating ligand that can oxidise alcoholic substrates in gas phase
These results point to the carboxylate donor in the first coordination sphere of iron catalysts and enzymes having an important role in tuning oxidant activation.

**Scheme 7.1.** Selective switching between Hydrogen Atom Abstraction (HAT) or Oxygen Atom Transfer (OAT) pathways in substrate oxidation using the mono-carboxylato ligand, tpena. When tpena acts as a pentadentate ligand, a dangling pyridyl group functions as a second coordination sphere base. Undemanding steric requirements of tpena means an additional endogenous monodentate ligand (e.g. the oxidant PhIO is shown) can coordinate to a high spin ($S = 5/2$) seven coordinated iron atom. The iron(III) resting state is $S = 5/2$ and $S = 1/2$ for mer-[Fe(tpena)]$^{2+}$ and fac-[Fe(tpena)]$^{2+}$ (not shown) respectively.

The iron(III) complex of $N,N,N'$-tris(2-pyridylmethyl)ethylenediamine-$N'$-acetate (tpena, Scheme 7.1) is remarkable in its tunable reactivity for substrate oxidation by Fe(III) oxidant adducts or their iron(IV)-oxo derivatives: Highly efficient catalytic reactions can be directed either exclusively toward Hydrogen Atom Abstraction (HAT) or Oxygen Atom Transfer (OAT) mechanisms depending on the choice of terminal oxidant and reaction conditions. Both reaction types are pertinent for rationalizing the impressive scope of reactivity found for the non-heme enzymes and the Fe(tpena) system is unique in its ability to effectively model both of these oxidative pathways. At first sight this is surprising given that tpena is a potentially coordinatively saturating hexadentate ligand. However, structural flexibility on the part of the ligand, and geometrical and spin-state flexibility on the part of the iron, play crucial roles. The tpena can act as a hexadentate N5O ligand in six- or seven-coordinated iron complexes ([Fe(tpena)]$^{2+}$, [FeOIPh(tpena)]$^{2+}$ and [FeOH(tpena)]$^{2+}$, and as a pentadentate N4O ligand in six-coordinated iron complexes ([FeCl(tpenaH)]$^{2+}$, and [Fe$_2$(O-O)(tpenaH)$_2$]$^{2+}$, $^{9,10,12,14}$). In this latter group one specific pyridyl arm is uncoordinated and protonated in all crystal structures. This allows for the creation of another important biomimetic motif – a second coordination sphere base.

Iron(III)-hydroperoxide and iron(III)-peroxide adducts of the iron complexes of the closely related 2-alkylpyridine substituted ethylenediamine-backboned neutral N5/N6 donor ligands (Rtpen = $N'$-alkyl-$N,N,N'$-tris(2-pyridylmethyl)ethylenediamine, $R$ = Me, Et, Bz, Pr, 'Pr, Ph, 2-methyl...
pyridine) as well as those for the aforementioned carboxylate-containing \([\text{Fe(tpena)}^{2+}\)] have been spectroscopically characterized.\(^7\) A significant difference in the chemistry of these comparative N5/N6 and NSO systems is evident. For example, \([\text{Fe(tpena)}^{2+}\)] catalyses highly effective alcohol oxidation by \(\text{H}_2\text{O}_2\) and in the absence of alcohol or another substrate, \(\text{H}_2\text{O}_2\) disproportionation.\(^8\) By contrast the N5/N6 ligand supported \([\text{Fe(Rtpen)}^{2+}\)] systems neither catalyse \(\text{H}_2\text{O}_2\) disproportionation or alcohol oxidation by \(\text{H}_2\text{O}_2\). In fact, methanol can be used as a solvent for observing transient \([\text{Fe}^{II}\text{OOH(Rtpen)}^{2+}\)] where half-lives of min to h (rt) are found for these complexes. In understanding the effects of the introduction of a carboxylate group into the first coordination sphere of the iron atom for the activation of terminal oxidants located cis to this donor, we now turn to the activation of alkyl hydroperoxides and peracids by \([\text{Fe(tpena)}^{2+}\]).

Understanding the reactivity of alkyl peroxides is important because they are used as initiators for curing (polymerization) resins and two component paints.\(^18\) This process involves mixing alkyl peroxide solutions with the vinylester/styrene resin containing any of a wide range of metal catalysts. Alkyl peroxides are used specifically for these applications since they are believed not to undergo disproportionation with the consequent limitations on shelf-life, as is the case for the cheaper oxidant \(\text{H}_2\text{O}_2\).\(^19\) Solutions containing cumene hydroperoxide are sold under the trademark Trigonox\(^\text{®}\) K-90 or Trigonox\(^\text{®}\) 239a. Alkyl peroxides are used also extensively as a terminal oxidants in industrial and laboratory scale organic syntheses.\(^20\)–\(^28\) Disproportionation of the alkyl peroxides has been sporadically suggested as a possible reason for reduced yields in catalytic selective substrate oxidations,\(^29\)–\(^32\) however the impact of unproductive reactions has never been evaluated in detail nor the release of product \(\text{O}_2\) directly measured.

Here we describe the spectroscopic detection of catalytically competent iron(III)alkylperoxide adducts of \([\text{Fe(tpena)}^{2+}\]), their decay product, \([\text{Fe}^{IV}\text{O(tpenaH)}^{2+}\]), along with concomitantly produced organic radicals that are present in working solutions. ROOH dismutation is unexpected in contrast to \(\text{H}_2\text{O}_2\) dismutation which is commonly catalysed by metal salts and complexes.\(^33\)–\(^37\) The quantification of the products of the disproportionation of ROOH, and an analysis of competing selective C-H oxidation reactions involving the R group or an external C-H substrate allows us to propose a common mechanism for \([\text{Fe(tpena)}^{2+}\])-catalysed \(\text{H}_2\text{O}_2\) and ROOH dismutation and external substrate C-H oxidations. Significantly, the reactivity patterns imply radical character for \([\text{Fe}^{IV}\text{O(tpenaH)}^{2+}\]), reinforcing our recent observation when this species is produced electrochemically in the absence of terminal chemical oxidants.\(^11\) In this case the reactivity of this carboxylate coordinated iron(IV)oxo towards C-H substrates with increasing C-H bond dissociation energies parallel that of the hydroxo (HO\(^\bullet\)) radical, albeit with slower rates, no doubt due to size. The results presented here broaden significantly the scope of reactivity observed for non-heme iron models.

**Experimental Section**

**Materials and Preparation**

\(N,N,N'-\text{tris(2-pyridylmethyl)ethylenediamine-}N'\text{-acetic acid (tpenaH) and [Fe}_2\text{O(tpenaH)}_2\text{]}\text{(ClO}_4\text{)}_4\text{(H}_2\text{O)}_2\text{] and [FeCl(Metpen)]PF}_6\text{ (Metpen = N-methyl-}N,N',N'\text{-tris(2-}]

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pyridylmethyl)ethane-1,2-diamine) were prepared as previously described. Solutions of \(^{1}\)BuOOH (70 % in \(\text{H}_2\text{O}\)), \(^{1}\)BuOOH in decane (5.5 M) and cumyI00H (88 % in cumene) were used as well as \(m\)-CPBA (77% in \(m\)-CBAH). Iodometric titrations and NMR spectroscopy were used to confirm the concentration and purity of the peroxide solutions. \(^{18}\text{O}\)-H\(_2\text{O}\) was supplied by Rotem Industries Ltd., and all other chemicals were purchased from Sigma-Aldrich.

**Generation of \([\text{Fe(OOR)}(\text{tpenaH})]\)\(^{2+}\) (\(R = \text{C(CH}_3\text{)}_3, \text{C(CH}_3\text{)_2Ph, C(O)PhCl}\))**

\([\text{Fe}_2\text{O}(\text{tpenaH})_2]\)\((\text{ClO}_4)_4(\text{H}_2\text{O})_2\) was dissolved in acetonitrile and the solution was allowed to equilibrate for 15 min in order to maximise the concentration of the solution state monomeric species \([\text{Fe(tpena)}]\)\(^{2+}\) that is derived by dehydration of the hemihydrate \([\text{Fe}_2\text{O}(\text{tpenaH})_2]\)\(^{4+}\). Solutions of alkyl or acyl hydroperoxide were subsequently added to generate \([\text{Fe(OOR)}(\text{tpenaH})]\)\(^{2+}\). Spectroscopic characterization with UV/vis, rRaman, EPR and Mössbauer spectroscopy were performed on 2-5 mM [Fe] solutions with 50 eq. alkyl or acyl hydroperoxide at either 5, -15 or -25 °C. Catalytic experiments were performed on 1 mM [Fe(tpena)]\(^{2+}\) (d\(_3\)-MeCN) with 750 eq. alkyl- or acyl-hydroperoxide and 750 eq. benzyl alcohol or toluene at rt. Volumetric measurements are performed at rt on either 0.5 mM [Fe] with 1,000 eq. oxidant or 25 \(\mu\)M [Fe] with 20,000 eq. oxidant (time-dependent detection).

**Instrumentation**

UV-vis spectra were recorded in 1 cm quartz cuvettes on either an Agilent 8453 spectrophotometer with an UNISOKU CoolSpeK UV USP-203 temperature controller or with an Analytikjena Specord S600 with a Quantum Northwest TC 125 temperature controller. Raman spectra were recorded in 1 cm quartz cuvettes with temperature control using a Flash300 (Quantum Northwest) at either 532 nm (300 mW at source, Cobolt Lasers) or at 785 nm using a Perkin Elmer RamanFlex fiber optic coupled Raman spectrometer (90 mW at sample). Data were recorded and processed using Solis (Andor Technology) with spectral calibration performed using the Raman spectrum of MeCN/toluene (50:50 V/V). 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. eview4wr and esimX were used for simulation. \(^1\)H NMR (400.12 MHz) and \(^{13}\text{C}\) NMR (100.61 MHz) spectra were recorded on a Bruker Avance III 400 spectrometer at ambient temperature. Chemical shifts are denoted relative to the residual solvent peak (d\(_3\)-MeCN, \(\delta_H = 1.94 \text{ ppm and } \delta_C = 1.32 \text{ ppm}\)), and the catalytic experiments were performed directly in MeCN-d\(_3\) on 1 mM [Fe] solutions. Substrate conversion is based on integrals of the aromatic protons. Head-space FTIR spectra were recorded in sealed 1 cm quartz cuvettes on a JASCO FT-NIR/MIR-4600 spectrometer, and the CO\(_2\) signal was quantified as previously described. Mössbauer spectra were recorded at 80K on a conventional spectrometer with alternating constant acceleration of the \(\gamma\)-source. Isomer shifts are denoted relative to \(\alpha\)-iron at 298 K, and the sample temperature was maintained constant in an Oxford Instruments Variox cryostat. The \(\gamma\)-source (57Co/Rh, 1.8 GBq) was kept at room temperature. The mf.SL package was used to fold the spectra hereby merging the two linear halves of the raw data and to eliminate the parabolic background as well as fitting the data. ESI-MS spectra were recorded in high-resolution positive mode with a Bruker microTOF-QII mass spectrometer. MIMS spectra were recorded using a Prisma quadrupole mass spectrometer (Pfeiffer Vacuum, Asslar, Germany). A flat sheet membrane (250 \(\mu\)m) of polydimethyl siloxane (Sil-Tec sheeting, Technical Products, Decatur, GA,
USA) separated the vacuum chamber (1x10^{-6} mbar) from the solution in the sample chamber (total volume 2.5 mL), which was equipped with magnetic stirring. The reaction chamber was filled with solutions of [Fe(tpena)]^{2+}, and the alkyl peroxide was injected directly to the solutions in the sample chamber as the resulting gas evolution was simultaneously measured. The data were recorded and processed using Quadstar 422 (Pfeiffer Vacuum, Asslar, Germany). Volumetric measurements were performed using a two-neck round-bottom flask with a stopcock-equipped gas delivery tube connected to a gas-measuring burette (± 0.1 mL). The peroxides were injected through a septum, and the evolved O_2 was volumetrically measured as a function of time. The rate constants reported represent the mean value of minimal double determinations which fall within ± 5%. Analyte solutions of peroxide (500 μL), 1.64 M KI(aq) (5 mL), 20 % H_2SO_4(aq) (5 mL) and H_2O (25 mL) were prepared for iodometric titrations (± 0.1 mL). An ammonium molybdate solution (0.5 mL, prepared from (NH_4)_6Mo_7O_24(9g), NH_3(aq) (28-30 %, 5 mL), NH_4NO_3 (24 g) and H_2O (5 mL)) and a starch solution (1 g/100 mL) were added as catalyst and indicator respectively. The mixture was titrated with 0.3 M Na_2S_2O_3(aq) and the analysis was repeated three times.

Results and Discussion
Iron(III)-alkyl Peroxides, [Fe(OOR)(tpenaH)]^{2+} R = C(CH_3)_3 and CH(CH_3)_2Ph
The solid state precursor for the solution state chemistry described below is the dark brown [(tpenaH)Fe(μ-O)Fe(tpenaH)][ClO_4]_4. On dissolution this oxo-bridged complex equilibrates with monomeric species; a hydrate, [Fe^{III}(OH)(tpenaH)]^{2+} and a dehydrate, [Fe^{III}(tpena)]^{2+}. Cleavage of the oxo-bridge is accompanied by a colour change from yellow-brown (λ_{max} 258 nm) to red-orange (λ_{max} 360 nm) in acetonitrile and takes ca. 15 min to equilibrate at rt. The addition (50 eq.) of tert-butyl hydroperoxide ('BuOOH, 70 % aq. solution) or cumene hydroperoxide (cumylOOH, 88 % solution) to these equilibrated solutions triggers an immediate colour change to purple (λ_{max} 558 nm) or red (λ_{max} 531 nm), respectively (Figure 7.1a, Table 7.1). Gas evolution is concomitant. This is predominantly O_2, vide infra. The chromophores are ascribed to the transient species [Fe(OOtBu)(tpenaH)]^{2+} and [Fe(OOcumyl)(tpenaH)]^{2+} respectively. With reference to the crystal structures of [Fe(Cl)(tpenaH)]^{2+}, [tpenaH]Fe(μ-O)Fe(tpenaH)][ClO_4]_4 and [V(O)(tpenaH)]^{2+}, the incoming ROOH is proposed to form a “charge-separated” adduct with [Fe(tpena)]^{2+}, i.e., the alkylperoxide is deprotonated and bound to iron(III) and the proton protonates an uncoordinated pyridine group. While it seems that an initial dehydration of the starting hemihydrate is necessary to observe these transients, counterintuitively, the formation of the iron-alkylperoxide adducts are dependent on the presence of a small amount of water. [Fe(OOtBu)(tpenaH)]^{2+} is not detected if the 'BuOOH is supplied in decane (5.5 M). If, however, 4 eq. water are introduced to the equilibrated acetonitrile solutions containing monomeric [Fe(tpena)]^{2+} immediately prior to the addition of the decane solution of 'BuOOH, the formation of the iron alkyl peroxide species is reinstated. These observations suggest that it is the mononuclear hydrate, [Fe(OH)(tpenaH)]^{2+} rather than [Fe(tpena)]^{2+} that is the immediate precursor for reaction with ROOH, and that the reaction involves substitution of a hydroxo ligand by the incoming alkylperoxide (Scheme 7.2) rather than an alkylperoxido displacement of a chelating pyridine group as would be the case if [Fe(tpena)]^{2+} was the immediate precursor. We have previously...
shown that two diastereoisomers (a *mer* and *fac* in terms of the three pyridine donors) for 
[Fe(tpena)]$^{2+}$ co-exist in solution.$^{8,10}$ Hydration will convert them to the same conformer and the 
simlicity of the spectroscopy, *vide infra*, supports the formation of only one diastereoisomer for 
the alkylperoxide adducts. Our representation of [Fe(X)(tpenaH)]$^{2+}$, X=OH, OO$^t$Bu, OOcumyl 
(Scheme 7.2) depicts therefore the diastereoisomer containing the pentadentate tpena 
conformation analogous to that found in all the known crystal structures of (MX(tpenaH))$^{n+}$.$^{8-}
10,12,14$ In these, the glycol donor is located *cis* to the exogenous ligand which in turn is *trans* to 
the amine donor associated with the dipyridylamine moiety.$^{8,9,12}$

![Figure 7.1](image-url)  
**Figure 7.1.** Spectroscopic data of the [Fe(OOR)(tpenaH)]$^{2+}$ generated by addition of 50 eq. *BuOOH or cumylOOH to 
[Fe(tpena)]$^{3+}$ in MeCN. (a) UV-vis absorption spectra (5 °C) of [Fe(OO$t$Bu)(tpenaH)]$^{2+}$ (blue, [Fe] = 2 mM) and 
[Fe(OOcumyl)(tpenaH)]$^{2+}$ (red, [Fe] = 4 mM). Insert: Photograph of frozen samples of [Fe(OO$t$Bu)(tpenaH)]$^{2+}$ and 
[Fe(OOcumyl)(tpenaH)]$^{2+}$. (b) EPR spectrum (black) recorded on a frozen solution of [Fe(OO$t$Bu)(tpena)]$^{2+}$ in MeCN at 
110 K. Microwave frequency 9.314212 GHz. Fitted data for [Fe(OO$t$Bu)(tpenaH)]$^{2+}$ and the *t*BuOO$^•$ radical are shown in 
blue and green, respectively. (c) Resonance Raman spectra of [Fe(OO$t$Bu)(tpenaH)]$^{2+}$ (blue, $\lambda_{exc}$ = 785, -25°C, 3 mM) 
and its decay product (purple, $\lambda_{exc}$ = 785), and [Fe(OOcumyl)(tpenaH)]$^{2+}$ (red, $\lambda_{exc}$ = 532, -25°C, 2 mM) and its decay 
product (orange, $\lambda_{exc}$ = 532). * = solvent band from MeCN, # = bands from either *BuOOH or cumylOOH. The spectra 
are normalized to the solvent band at 919 cm$^{-1}$.

**Table 7.1.** Spectroscopic properties for [Fe$^{III}$OOR(tpenaH)]$^{2+}$

<table>
<thead>
<tr>
<th>R</th>
<th>$\lambda_{max}$</th>
<th>$\nu_{Fe-O}$</th>
<th>$\nu_{O-O}$</th>
<th>$g$-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH(CH$_3$)$_3$</td>
<td>558</td>
<td>675</td>
<td>786</td>
<td>2.20, 2.12, 1.97</td>
</tr>
<tr>
<td>CH(CH$_3$)$_2$Ph</td>
<td>531</td>
<td>684</td>
<td>782</td>
<td>2.19, 2.12, 1.97</td>
</tr>
<tr>
<td>C(O)m-ClPh</td>
<td>565</td>
<td>*</td>
<td>*</td>
<td>2.23, 2.18, 1.95</td>
</tr>
</tbody>
</table>

* Lifetime too short for measurement at -40 °C.
The iron(III)-alkylperoxide species are short-lived at room temperature (seconds), however a $T_{1/2}$ of 30 and 20 s for $[\text{Fe}(\text{OO}^t\text{Bu})(\text{tpenaH})]^{2+}$ and $[\text{Fe} (\text{OO}^\text{cumyl})(\text{tpenaH})]^{2+}$ respectively are measured at 5 °C (SI Figure 7.S1). At -30 °C both species can be detected for several minutes using the same ratios and concentrations of reagents. Solutions containing ca. 10 % water gave the maximum yield in terms of the lifetime of the alkyl peroxides, which increased from 3 min to 6 min at -15 °C. EPR spectra of frozen solutions shows rhombic signals with $g = 2.20, 2.12, 1.97$ and $g = 2.19, 2.12, 1.97$ for $[\text{Fe}(\text{OO}^t\text{Bu})(\text{tpenaH})]^{2+}$ (Figure 7.1b) and $[\text{Fe} (\text{OO}^\text{cumyl})(\text{tpenaH})]^{2+}$ (SI Figure 7.S2), respectively, indicating low-spin iron(III) ($S = ½$) species. Resonance Raman spectra show enhanced bands at 675 and 786 cm$^{-1}$ for $[\text{Fe}(\text{OO}^t\text{Bu})(\text{tpenaH})]^{2+}$ and at 684 and 782 cm$^{-1}$ for $[\text{Fe} (\text{OO}^\text{cumyl})(\text{tpenaH})]^{2+}$ (Figure 7.1c). Based on comparison with the spectra of previously reported low-spin mononuclear non-heme iron(III) alkyl peroxide species, these bands can be associated with the Fe-O and O-O bonds respectively. The visible absorbance bands are red-shifted compared to the hydroperoxide derived species $[\text{Fe}(\text{OOH})(\text{tpenaH})]^{2+}$ ($\lambda_{\text{max}}$ 520 nm). The O-O stretch of the $[\text{Fe}(\text{OOR})(\text{tpenaH})]^{2+}$ complexes were not shifted compared to that observed for $[\text{Fe}(\text{OOH})(\text{tpenaH})]^{2+}$ (788 cm$^{-1}$), whereas the Fe-O stretches are found at 70 cm$^{-1}$ higher wavenumbers suggesting a comparatively stronger Fe-O bond. A similar trend was noted for the Raman shift of the homologous $[\text{Fe}(\text{OOR})(\text{TPA})(\text{solvent})]^{2+}$ ($R = \text{H},^t\text{Bu}$) pair. A band at 484 cm$^{-1}$ for $[\text{Fe}(\text{OOR})(\text{tpenaH})]^{2+}$, can be assigned to a combined O-C-C/C-C-C bending vibration from the $^t\text{Bu}$ group.

Evidence for Homolytic FeO-OR Bond Cleavage in Alkylperoxide Adducts

The decay of the $[\text{Fe}(\text{OOR})(\text{tpenaH})]^{2+}$ complexes proceeds by homolytic cleavage of the Fe$^{IV}$O-OR bond. This conclusion is supported by the evolution of the characteristic 730 nm band$^{11,12}$ for $[\text{Fe}^\text{IV}O(\text{tpenaH})]^{2+}$ (Figure 7.2a). Combined time-resolved UV-vis and rRaman spectroscopy of the decaying $[\text{Fe}^\text{IV}OOR(\text{tpenaH})]^{2+}$ species shows that a resonance enhanced band at 863 cm$^{-1}$ (Figure 7.1c) can be correlated to the 730 nm band in the UV-vis spectrum and it is therefore assigned to a $\nu_{\text{Fe}=\text{O}}$ stretch. This value is higher than Raman shifts previously reported for non-heme iron(IV)oxo species which typically occur in the range 790-850 cm$^{-1}$ for both $S = 1$ and $S = 2$ systems,$^{44}$ suggesting an Fe=O bond that is stronger than typically found for non-heme iron(IV)oxo systems. We speculate that the bond possesses partial triple bond character analogous to that proposed for vanadyl complexes$^{45-47}$. Significantly, isotropic signals at $g = 2.02$ (Figure 7.1b) and $g = 2.00$ (SI Figure 7.S2) for $[\text{Fe}(\text{OO}^t\text{Bu})(\text{tpenaH})]^{2+}$ and
Catalytic Alkyl Hydroperoxide and Acylperoxide Disproportionation by a Nonheme Iron Complex

[Fe(OOcumyl)(tpenaH)]$^{2+}$ respectively, overlap with the signals from the low-spin Fe(III)-hydroperoxide adducts in the EPR spectra. These are due to production of an organic radical. Homolysis of the Fe$^{III}$O-OR bond produces the immediate sister products [Fe$^{IV}$O(tpenaH)]$^{2+}$ and the alkoxide radicals •O'Bu or •OOC(CH$_3$)$_2$Ph, respectively. These latter species can be expected to be too short-lived for detection and in the presence of excess ROOH they can be expect to abstract a peroxy H atom to give *OO'Bu and *OOC(CH$_3$)$_2$Ph, respectively along with the derived alcohol.$^{48,49}$ The isotropic EPR signals are therefore assigned to these generated peroxy radicals rather than the directly produced alkoxide radicals. Signals due to the Fe(IV)oxo species and the organic radicals are present concurrently with those for [Fe(OOR)(tpenaH)]$^{2+}$ (Figure 7.1b and 7.2b) indicating similar stabilities for the two iron-based transients. Supporting the co-existence of iron(III) hydrates, an iron(III)alkylperoxide and an iron(IV)oxo species is a Mössbauer spectrum (SI Figure 7.S3) of [Fe(OH)(tpenaH)]$^{2+}$ and 50 eq. cumylOOH, frozen 20 s after mixing. This can be fitted to [Fe(OH)(tpenaH)]$^{2+}$ (δ = 0.14 mm·s$^{-1}$, ΔE$_Q$ = 2.08 mm·s$^{-1}$, 22%), [Fe$_2$O(tpenaH)$_2$]$^{4+}$ (δ = 0.43 mm·s$^{-1}$, ΔE$_Q$ = 1.60 mm·s$^{-1}$, 26%) and [Fe$^{IV}$O(tpenaH)]$^{2+}$ (δ = 0.00 mm·s$^{-1}$, ΔE$_Q$ = 0.90 mm·s$^{-1}$, 24%) which have been independently characterized previously by Mössbauer spectroscopy.$^{12}$ This has allowed for assignment of a fourth species to the low-spin iron(III)alkylperoxo complex [Fe(OOcumyl)(tpenaH)]$^{2+}$ (δ = 0.20 mm·s$^{-1}$, ΔE$_Q$ = 2.00 mm·s$^{-1}$, 28%). These parameters are quite similar to those for [Fe(OOH)(tpenaH)]$^{2+}$ (δ = 0.21 mm·s$^{-1}$, ΔE$_Q$ = 2.08 mm·s$^{-1}$)$^8$. After their decay, all species, [Fe(OOR)(tpenaH)]$^{2+}$, [Fe$^{IV}$O(tpenaH)]$^{2+}$ and the organic radicals, are regenerated by addition of further portions (50 eq.) of alkyl hydroperoxides, Figure 7.2b.

*Figure 7.2. Conversion of [Fe(OO'tBu)(tpenaH)]$^{2+}$ to [Fe$^{IV}$O(tpenaH)]$^{2+}$ (50 eq. *tBuOOH, [Fe] = 2 mM, 5 °C. (a) Time-dependent UV-vis absorption spectra. Inset: time-trace for absorbance at 558 nm (blue) and 730 nm (green) and (b) Time dependence of absorbance at 558 nm and 730 nm as portions of 50 eq. *BuOOH are added every 100 s to regenerate [Fe(OO'tBu)(tpenaH)]$^{2+}$ and [Fe$^{IV}$O(tpenaH)]$^{2+}$.*

The repeatable cyclability is evidence that tpena is not oxidatively degraded and this stands in contrast to the dismutation reaction of H$_2$O$_2$ catalysed by [Fe(tpena)]$^{2+}$ where tpena will start decomposing when the substrate H$_2$O$_2$ is not present in a large excess, or alternatively, if an easily oxidizable sacrificial substrate is not provided.$^8$ In the present case the organic groups of the alkyl hydroperoxides offer built-in sacrificial exogenous substrates to compete with the alkyl hydroperoxide dismutation and herewith effectively competitively inhibit tpena degradation. The solid state precursor [[(tpenaH)Fe(μ-O)Fe(tpenaH)]ClO$_4$]$_4$ can be quantitatively recovered after the consumption of thousands equivalents of alkyl peroxides.
Catalytic Alkyl Hydroperoxide Disproportionation and Competing Radical Reactions

Simultaneous with detection of \([\text{Fe}^{III}(\text{OOR})(\text{tpenaH})]^2+\) and \([\text{Fe}^{IV}\text{O}(\text{tpenaH})]^2+\), colourless gas production is visible as bubbles when the alkyl peroxides are added in excess to \([\text{Fe}(\text{OH})(\text{tpenaH})]^2+\) in acetonitrile (e.g., 50 eq. ROOH to 0.5 mM [Fe]). See video in SI. Membrane-Introduction Mass Spectrometry (MIMS) (m/z 32, Figure 7.3a) and head-space Raman spectroscopy (O=O band at 1556 cm\(^{-1}\), Figure 7.3b) confirmed that this is predominantly \(\text{O}_2\). That this was result of water oxidation of adventitious water and that provided in the aqueous solutions of peroxides was excluded due to inappropriately large amounts of \(\text{O}_2\) released compared to the water available, and the lack of \(^{18}\text{O}\) incorporation in the evolved \(\text{O}_2\),\(^{50}\) when \(^{18}\text{O}\)-labelled water was added to mixtures. In addition, this experiment demonstrates that the rate of ROOH disproportionation is faster than any potential O atom exchange between water and the \([\text{Fe}^{IV}\text{O}(\text{tpenaH})]^2+\): The evolved \(\text{O}_2\) derives exclusively from the disproportionation of the alkyl hydroperoxides, and the reaction is catalytic. \(\text{O}_2\) in lower yields, evolves also when water is the sole solvent, however, in this case the iron-based transients cannot be observed. The oxo-bridged complex dominates the speciation in these solutions, and this observation supports the conclusion that this cannot directly activate ROOH and corroborates the deduction that the catalytically competent resting state complex is \([\text{Fe}(\text{OH})(\text{tpenaH})]^2+\). The addition of 1000 eq. \(^1\text{BuOOH}\) (aq. 70 %) to a \([\text{Fe}(\text{tpena})]^2+\) solution (3 mL 0.5 mM) results in the production of 15.5(2) mL of gas (table 7.2). Addition of a second portion of 1000 eq. results in a release of another 15.5(2) mL. This includes a very small amount of \(\text{CO}_2\), vide infra, and when this is accounted for, the yield of \(\text{O}_2\) is approx. 88 % (assuming that two mole \(^1\text{BuOOH}\) are required to yield one mole of \(\text{O}_2\)). The equivalent experiment using cumylOOH gives a lower yield of \(\text{O}_2\) at 44 % (8.0 mL). Concurrent tert-butanol and cumyl alcohol production as the major organic products, respectively, were confirmed using NMR spectroscopy to follow in situ reactions in \(d_3\)-MeCN. Spectra recorded 1 h after the addition of alkyl hydroperoxide showed that the \(^1\text{BuOOH}\) and cumylOOH were fully consumed and gas evolution had ceased (SI Figures 7.S4 and 7.S5).

Table 7.2. Volumetric measurements of \(\text{O}_2\) and \(\text{CO}_2\) were performed on 0.5 mM \([\text{Fe}(\text{OH})(\text{tpenaH})]^2+\) with the addition of either \(^1\text{BuOOH}\), cumylOOH or \(m\)-CPBA (1000 eq.). The ratio of organic products were determined by in-situ NMR experiments using \([\text{Fe}(\text{OH})(\text{tpenaH})]^2+\) (1 mM in MeCN-\(d_3\)) and the addition of 750 eq. oxidant.

<table>
<thead>
<tr>
<th>V(_{\text{gas}}) [ml]</th>
<th>Yield of (\text{O}_2) adjusted for (\text{CO}_2) release</th>
<th>Ratio of ROOH and products after 1 hr reaction time in the absence of external substrates (\text{ROOH} : \text{ROH} : \text{ketone})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^1\text{BuOOH})</td>
<td>15.5 ± 0.2</td>
<td>15.1 (0.95 : 0.05)</td>
</tr>
<tr>
<td>cumylOOH</td>
<td>8.0 ± 0.4</td>
<td>7.6 (0.70 : 0.30)</td>
</tr>
<tr>
<td>(m)-CPBA</td>
<td>4.0 ± 0.4</td>
<td>3.7 (0.50 : 0.50 : 0)</td>
</tr>
</tbody>
</table>

Sugimoto and Sawyer\(^{51}\) have shown that simple iron perchlorates catalyse \(\text{H}_2\text{O}_2\) dismutation in acetonitrile under anhydrous conditions. In a significant contrast they do not promote \(^1\text{BuOOH}\) or \(m\)-chloroperoxybenzoic acid \((m\)-CPBA\) disproportionation.\(^{52}\) Our checks as a control for the present context verify this earlier work, also when water is present. In lieu of a known catalyst for \(^1\text{BuOOH}\) disproportionation with which to compare the efficiency of \([\text{Fe}(\text{tpena})]^2+\) we tested \([\text{FeCl}(\text{Metpen})]\)PF\(_6\) for its ability to catalyse this reaction. This complex is a highly pertinent system for comparison since with its ethylene backbone it is structurally related and importantly iron(III) hydroperoxide adducts have been characterised for this and related Rtpen (R = Me, Bz, Et, Pr, 'Pr, Ph) species.\(^{15-17,53-55}\) Using the same ratios of \([\text{FeCl}(\text{Metpen})]^+\): \(^1\text{BuOOH}\)
and conditions as those above for the Fe-tpena system ([Fe] = 0.5 mM, 1000 eq. tBuOOH) we found no detectable disproportionation of tBuOOH, i.e., over 30 minutes no O₂ had evolved.

Figure 7.3. Detection of evolved O₂ and CO₂ when ROOH is added to [Fe(OH)(tpenaH)]²⁺ in MeCN (a) MIMS spectra of [Fe(OH)(tpenaH)]²⁺ (black) and with the addition of 50 eq. cumylOOH after 2 min (red) and 12 min (blue). The broad peak between m/z = 35-42 is due to acetonitrile. The m/z = 43 signal originates from unreacted cumylOOH passing through the membrane. Insert: time dependence of the ion current for the ions O₂•⁺ (m/z 32). [Fe] = 0.5 mM. (b) Time-trace of the O₂ evolution (1556 cm⁻¹) with head-space Raman spectroscopy (λₐₑₓ = 532 nm) with the addition of two portions of 100 eq. tBuOOH. [Fe] = 2 mM. The arrows indicate addition of tBuOOH. Build-up of pressure in the sealed cuvette prevented further additions of the peroxide to the closed system, however the gas evolution can be re-initiated more than 10 times using an open vessel. (c) Time-dependent volumetric detection of the gas release with the addition of 20,000 eq. oxidant to 25 μM [Fe(OH)(tpenaH)]²⁺ solutions in MeCN. tBuOOH (blue), cumylOOH (red), m-CPBA (green) (d) Time-resolved head-space FTIR spectroscopy showing the evolution of CO₂ over time after addition of 1000 eq. of cumylOOH. Time-dependence of absorbance at 2360 cm⁻¹. Red: 1000 eq. cumylOOH, blue: 1000 eq. tBuOOH. [Fe] = 0.5 mM. The bands at 2253 and 2292 cm⁻¹ are due to acetonitrile.

Volumetric monitoring of the release of the O₂ as a function of time revealed that the initial rate constants are 3.66(6) mMs⁻¹ and 0.29(8) mMs⁻¹ (3 mL 25μM [Fe] and 20,000 oxidant/substrate) for the addition of tBuOOH and cumylOOH, respectively, hence the initial rate is 12 times faster for tBuOOH (Figure 7.3c). The O₂ release ceases after 5 min when employing tBuOOH, whereas this takes several hours when cumylOOH is used under the same concentrations. At constant complex concentration saturation kinetics were not observed on the addition of 6500 – 30000 eq. of tBuOOH, and the relationship between catalyst concentration and the rate constants is non-linear: A doubling of the iron concentration results in a more than doubling of the rate constants (SI Figure 7.S6-S8). The initial lag time before the O₂ releases is rationalized by the need to establish a steady-state concentration of [FeIVO(tpenaH)]²⁺ and the alkoxy radical. As
mentioned both \( \text{tBuO}^* \) and \( \text{cumylO}^* \) will abstract an H atom from the excess \( \text{tBuOOH} \) and \( \text{cumylOOH} \) respectively to form the EPR detectable secondary radicals \( \text{tBuOO}^* \) and \( \text{cumylOO}^* \). Acetone and acetophenone, respectively, are detected by NMR spectroscopy as the expected minor organic products from the disproportionation reactions (table 7.2, SI Figure 7.S4 and 7.S5). The formation of these ketone products occurs by \( \beta \)-scission reactions of the alkoxyl radical. In the case of \( \text{tBuOOH} \), the acetone formation amounts to ca. 5 % of the organic products, whereas for \( \text{cumylOOH} \) the yield of acetophenone is greater at approximately 30 %. This is readily rationalised by the lower stability of \( \text{cumylO}^* \) compared with \( \text{tBuO}^* \).\(^{56}\) Hence the \( \beta \)-scission pathway, being unimolecular, is more pronounced when \( \text{cumylOOH} \) is a substrate and hence \( \text{cumylOOH} \) disproportionation is less favoured than the disproportionation of \( \text{tBuOOH} \). Addition of further portions of alkyl hydroperoxides re-initiates \( \text{O}_2 \) evolution (Figure 7.3b) concomitant with the visible regeneration of the iron(III)-peroxide species (Figure 7.2b). The catalyst is robust.

As mentioned in the introduction, the cause of low yields in redox active metal (Rh, Fe)-complexes catalysing oxidations of organic substrates by alkyl hydroperoxides have sporadically been ascribed - without experimental verification - to a putative background dismutation.\(^{29–31}\) Aside from the oxidation of organic substrates, alkyl hydroperoxides are routinely used in the preparation of high-valent metal complexes. In these syntheses it would seem that ample opportunities for the observation of disproportionation have been available to the many workers in the area of high valent biomimetic first row transition metal complexes: The dearth of observations of this specific reaction is surprising. Over two decades ago Caudle et al. showed that \( \text{Mn}^{III}(2\text{-OHsalpn})_2, \text{ (2-OHsalpn = 1,3-bis(salicylideneamino)-2-propanol)}^{57} \) reacts with \( \text{tBuOOH} \) to give a \( \text{Mn}^{III}(\text{O})\text{Mn}^{IV} \) complex. These authors assumed that the concurrently produced \( \text{tbutoxy} \) radical (undetected) reacts with excess \( \text{tBuOOH} \) to give the \( \text{tbutylperoxyl} \) radical (Eq. 1). Subsequent coupling of two \( \text{tbutylperoxyl} \) radicals was proposed as the source of the observed \( \text{O}_2 \) (Eq. 2). \( \text{O}_2 \) evolution from alkyl hydroperoxides was noted also when they are reacted with \( \text{[Fe(tpa)X}_2^{2+} \) and \( \text{[Fe}_2\text{O(tpa)}_2(\text{H}_2\text{O})_2]_4 \) \( \text{X} = \text{Cl, Br, tpa} = \text{tris(2-pyridylmethyl)amine})^{58} \). In these cases, peroxy H atom abstraction from ROOH to produce ROO\(^* \) by the iron(III)-tpa complex with concurrent reduction of the iron to the +2 state was proposed to initialise the reaction. Again, \( \text{O}_2 \) extrusion after the ROO\(^* \) coupling reaction in Eq. 2 was proposed. In contrast to the tpena-based system here, high valent iron is not involved. \( \text{O}_2 \) was not quantified in either of these studies so we cannot compare yields or rates. Neither of these reactions were studied in detail from the viewpoint of actual turnover or catalysis.

\[
\text{O}^*\text{Bu} + \text{tBuOOH} \rightarrow \text{tBuOH} + \text{OO}^*\text{Bu} \tag{1}
\]

\[
2 \text{OO}^*\text{Bu} \rightarrow \text{tBuOOOO} \text{Bu} \rightarrow \text{O}_2 + 2 \text{O}^*\text{Bu} \tag{2}
\]

While the coupling of \( \text{OOR} \) radicals (Eq. 2) might be one pathway to \( \text{O}_2 \), the reaction mixtures contain an abundance of competing substrates to potentially quench \( \text{OOR} \), not least the oxy-radical like \( \text{[Fe}^{\text{IV}}\text{O(tpenaH)}]^{2+} \). We propose that the major \( \text{O}_2 \) releasing step could predominantly involve the coupling of \( \text{[Fe}^{\text{IV}}\text{O(tpenaH)}]^{2+} \) with the abundantly present \( \text{OOCR} \). Extrusion of \( \text{O}_2 \) from a putative \( \text{[Fe}^{\text{III}}\text{OOOCR}(\text{tpenaH})]^{2+} \) reminiscent of the Russell mechanism’s dialkyltetroxide intermediate in Eq. 2,\(^{59} \) will collapse to \( \text{O}_2 \) and an iron(III)-alkoxide, \( \text{[Fe}^{\text{III}}\text{OCR}(\text{tpenaH})]^{2+} \) (Scheme 7.3 path g). The beauty of this proposal is that all the detected products are accountable by the pathways in Scheme 7.3.
Scheme 7.3. Catalytic alkyl hydroperoxide disproportionation using the [Fe(tpena)]^{2+} system. Entry in the cycle occurs by the charge separation addition of an alkyl hydroperoxide to form [Fe^{IV}O(tpenaH)]^{2+}. (a) Production of [Fe^{IV}O(tpenaH)]^{2+} and alkoxide radical by FeO-OCR₃ homolysis. (b) Reaction of alkylperoxide radical with [Fe^{IV}O(tpenaH)]^{2+} to form the putative [FeOOORC₃(tpenaH)]^{2+} (c) β-Scission of alkoxy radical. (d) Production of alkylperoxide radical and product alcohol or carboxylic acid. (e) Reaction of alkyl hydroperoxide with [Fe^{IV}O(tpenaH)]^{2+} to give alkylperoxide radical. (f) Ligand exchange of the alcohol adduct to give the alkyl hydroperoxide adduct of [Fe^{III}(tpena)]^{2+}. (g) O₂ expulsion and formation of the alkoxy adduct of the resting-state catalyst, [Fe^{III}OR(tpenaH)]^{2+}.

Concurrently with the alkyl hydroperoxide decomposition and generation of O₂ (m/z = 32), an increase of the peaks at m/z 29, 30, 31 and 44 in MIMS spectra are observed suggesting formation of one-carbon containing molecules (Figure 7.3a). Decomposition of tpena as the carbon source is excluded, because of (i) the repeatability over many cycles without loss of catalytic efficiency, (ii) the fact that [(tpenaH)Fe(μ-O)Fe(tpenaH)][ClO₄]₄ can be quantitatively recovered and, (iii) the ratio of the alkyl derived products of the reactions. Acetonitrile oxidation as source is also discounted due to the relatively high BDEs for H-CH₂CN and H₃C-CN (406 and 522 kJmol⁻¹)⁶⁰ as well as the obvious lack of correlation to concentration. The remaining, and most plausible option is that the methyl radical produced via the β-scission pathway is the source (Scheme 7.3, path c). This methyl radical can react with O₂ (which saturates the solutions) to give carbon monoxide, carbon dioxide, formaldehyde and methanol.⁶¹,⁶² The exact ratio between these products will be pressure and temperature dependent, however the growth of
ions at m/z 29, 30, 31 and 44 in the MIMS spectra for both alkyl hydroperoxides are consistent with formation of formaldehyde, methanol and CO$_2$ (SI Figure 7.S9). Crucially, the quantity of CO$_2$ is directly proportional to the amount of ROOH that was added initially. The yield was quantified by head-space FTIR spectroscopy to be approximately one CO$_2$ per 30 ROOH consumed (Figure 7.3d). This CO$_2$ accounts for a minor proportion of the gas evolved during the decomposition, and as mentioned above, the determination of O$_2$ yields has taken this into account.

**Competitive and Selective C-H Substrate Oxidation Reactions**

If toluene (750 eq.) is added before addition of tBuOOH (750 eq.) to [Fe(OH)(tpenaH]$^{2+}$, NMR spectroscopy verifies that it is oxidized to benzaldehyde (SI Figure 7.S10: $\delta_H$(CHO) = 10.00 ppm and $\delta_C$(CHO) = 193.7 ppm). After 1 h only trace amounts of tBuOOH remain, with tBuOH being the major product with traces of acetone. Based on the comparison of the integrals of the five aromatic protons in toluene and benzaldehyde, a 10 % conversion has occurred (TON = 38). Benzylalcohol, which is an intermediate on the reaction pathway from toluene to benzaldehyde, is not detected, presumably because of its facile onward oxidation. Benzoic acid is not detected suggesting that benzaldehyde is not easily oxidized under these conditions. Control reactions show that tBuOOH cannot oxidise toluene, benzyl alcohol or benzaldehyde in the absence of [Fe(tpena)]$^{2+}$.

The [Fe(OH)(tpenaH)]$^{2+}$/ROOH system furnishes highly selective catalysis of the oxidation of appropriate C-H bonds under appropriate limiting reagent conditions. A conversion of 47 % to benzaldehyde after 1 h is measured when benzyl alcohol is added to acetonitrile solutions in equivalent amounts to the subsequently added tBuOOH (PhCH$_2$OH : tBuOOH : [Fe(OH)(tpenaH)]$^{2+}$ = 750:750:1, TON = 352). Volumetric detection of the gas release under these conditions shows a decrease to 8.0 mL compared with the 15.5 mL that could be recovered if an external substrate is not added. Quantification of the CO$_2$ shows the same amount of CO$_2$ is produced as that in the absence of benzyl alcohol, thus the β-scission pathway is not suppressed in any significant way, and an adjusted yield of 44 % O$_2$ in the presence of equimolar amounts of tBuOOH and benzyl alcohol can be determined. This correlates nearly perfectly with the 47 % conversion of the benzyl alcohol to benzaldehyde detected by NMR spectroscopy. Hence PhCH$_2$OH (BDE for methylene C-H, 331 kJmol$^{-1}$) and tBuOOH (BDE 1 BuOO-H, 352 kJmol$^{-1}$) compete equally as substrates for [Fe$^{IV}$O(tpenaH)]$^{2+}$ despite the lower BDE for PhCH$_2$OH. This implies a polar effect on the HAT process promoting tBuOOH as an equal substrate. It is easy to envisage that the dangling pyridinium arm might participate through a supramolecular H bonding interaction with the distal O atom of the tBuOOH. A 1:5 ratio of tBuOOH : PhCH$_2$OH reduced the gas release further to a 25 % of the yield found in the absence of benzyl alcohol. The in situ oxidants responsible for the oxidation of toluene and benzyl alcohol are proposed to be all of [Fe$^{IV}$O(tpenaH)]$^{2+}$, RO$^•$ and ROO$^•$. These will all abstract H atoms from the aliphatic C-H bonds of these substrates to regenerate [Fe$^{III}$OH(tpenaH)]$^{2+}$ and ROOH, and produce ROH, along with benzyl radicals with which the generated O$_2$ might react directly.

**O$_2$ Evolution is Suppressed in the Reaction of Fe(III)-tpena with a Peracid**

The reaction of [Fe$^{III}$(OH)(tpenaH)]$^{2+}$ with m-CPBA (50 eq.) generates [Fe$^{IV}$O(tpenaH)]$^{2+}$ more rapidly compared to H$_2$O$_2$ and alkyl hydroperoxides as evidenced by the appearance of an
absorption band at 730 nm, detected only at low temperatures (-30 °C) where [FeVII(O(tpenaH))²⁺] shows a half-life or around 20 s. At -40 °C a barely perceptible shoulder at 565 nm is revealed (< 2 s, Figure 7.4a). This is likely due to [Fe(OOC(O)m-PhCl)(tpenaH)³⁺] and 50 eq. m-CPBA shows three distinct signals: a high-spin iron(III) (gₘₐₓ = 8.2, 5.2, 4.2), a rhombic low-spin iron(III) with g = 2.23, 2.18 and 1.95 (red) and an isotropic signal with g = 2.00 (blue). The latter two signals can, analogously with the alkyl peroxide reactions, be associated with the transient peroxycacid adduct [Fe(OOC(O)m-PhCl)(tpenaH)³⁺] and its daughter m-ClPhC(O)O· or derived m-ClPhC(O)OO· radical. The high-spin signal observed in the EPR spectrum has no counterpart in the reactions with ¹BuOOH or cumyLOOH and we propose this is due to [FeVII(O(OC(O)PhCl)(tpenaH))]²⁺, vide infra.

While some O₂ is detected, the reaction of [Fe(OH)(tpenaH)]²⁺ with 1000 eq. m-CPBA does not give rise to the release of large amounts of O₂ as it does in the reactions with ¹BuOOH and cumyLOOH (table 7.2). A yield of 23 % of the theoretical O₂ production (based on the mechanism in Scheme 7.3) is volumetrically detected after 30 min. The products of the disproportionation of m-CPBA are O₂ and m-chlorobenzoic acid (m-CBAH). Thus, X in Scheme 7.3 will be m-chlorobenzoyl. Corroborating, NMR spectra of mixtures containing Fe-tpena and m-CPBA (1:750) in d₇-MeCN show that m-CBAH is produced concurrently with consumption of the m-CPBA. After 1 h reaction time half of the m-CPBA has disappeared (SI Figure 7.511), but 25 % of the m-CPBA remains unreacted after 3 days. It is not unexpected that the product m-CBAH might inhibit the catalytic reaction to a far greater degree compared with the product alcohols from the alkylhydroperoxide disproportionation reactions, i.e. the species [Fe(OX)(tpenaH)]²⁺ in Scheme 7.3, in this case [FeVII(O(OC(O)PhCl)(tpenaH))]²⁺ is more stable than the counterpart [Fe(O'Bu)(tpenaH)]²⁺ and [Fe(Ocumyl)(tpenaH)]²⁺ complexes. This was verified by recording ESI-mass spectra of [Fe(tpena)]²⁺ solutions in the presence of 50 eq. ¹BuOH or m-CBAH. Both show a base peak at m/z = 446.1256 corresponding to [FeVII(tpena)]⁺ but, however the spectrum of the mixture containing m-CBAH contains also two intense peaks at m/z = 601.114 (59 %, calcd: 601.117 for C₂₅H₂₈ClFeN₅O₄) and m/z = 557.124 (39 %, calculated: 557.128 for C₂₉H₂₈ClFeN₅O₃) which correspond the m-CBA adduct ions, [FeVII(m-CBA)(tpena)]⁺ and [FeVII(m-CBA)(tpena)-CO₂]⁺, respectively (Figure 7.4c). These results show that the product m-CBAH inhibits step (f) in the catalytic cycle by formation of a relatively stable [FeVII(O(OC(O)PhCl)(tpenaH))]²⁺, Scheme 7.3. Commercial m-CPBA is significantly contaminated by m-CBAH so this inhibitor is actually present from the first addition of its derived peroxide. Consistently with the ESI-MS, UV-vis and EPR spectra of acetonitrile solutions of [Fe(tpena)]²⁺ are not affected by the addition of ¹BuOH whereas the addition of m-CBAH results in the disappearance of the characteristic band of [Fe(tpena)]²⁺ at λₘₐₓ = 360 nm. The EPR spectrum of this latter solution reproduces the high-spin signal (gₘₐₓ = 8.5, 5.2, 4.2, 3.0) of the working solutions where m-CPBA is the substrate, Figure 7.4b (SI Figure 7.512). It is therefore unambiguous that the EPR signal can be assigned to high spin (S = 5/₂) [FeVII(tpenaH)(m-CBA)]²⁺.
Figure 7.4. (a) UV-vis spectra of \([\text{Fe(tpena)}]^{2+}\) (orange) with the addition of \(m\)-CPBA (50 eq, \([\text{Fe}] = 2 \text{ mM}\)) at -40°C to generate \([\text{Fe(OOC(O)m-PhCl)(tpenaH)}]^{2+}\) (red) and \([\text{Fe}^{\text{IV}}=\text{O}(\text{tpenaH})]^{2+}\) (green). (b) EPR spectra recorded on a frozen solution of \([\text{Fe}(\text{OH})(\text{tpenaH})]^{2+}\) with the addition of 50 eq. \(m\)-CPBA in MeCN at 110K. Microwave frequency: 9.309872 GHz. Fitted data for \([\text{Fe(OOC(O)m-PhCl)(tpenaH)}]^{2+}\) and the \(m\)-ClPhC(O)O• or derived \(m\)-ClPhC(O)OO• radical are shown in red and blue, respectively. (c) ESI-MS of a solution of \([\text{Fe(tpena)}]^{2+}\) and \(m\)-CBA (1:50, MeCN). Assignments: \(m/z = 601.114, \text{calcd.} 601.117\) for \(C_{29}H_{28}ClFeN_{5}O_{4}, [\text{Fe}^{\text{III}}(\text{tpena})(m\text{-CBA})]^{+}\); \(m/z = 557.124, \text{calcd.} 557.128\) for \(C_{28}H_{28}ClFeN_{5}O_{2}, [\text{Fe}^{\text{III}}(\text{tpena})(m\text{-CBA})-\text{CO}]^{+}\); \(m/z = 388.119, \text{calcd.} 388.122\) for \(C_{20}H_{22}FeN_{5}, [\text{Fe}^{\text{II}}(\text{tpena})-\text{CH}_{2}\text{COO}]^{+}\); \(m/z = 465.075, \text{calcd.} 465.125\) for \(C_{22}H_{26}ClFeN_{6}, [\text{Fe}^{\text{II}}(\text{Cl})(\text{tpena})-\text{CH}_{2}\text{COO}](\text{MeCN})]^{+}\).

Conclusion

The Fe-tpena system, uniquely compared to all other known non-heme models, contains a chelating single carboxylato donor cis to the peroxide binding site. This is biomimetic with respect to the propensity of the occurrence of mono Asp/Glu coordination cis to \(O_2\) activating enzymatic non-heme sites. Transient low-spin iron(III)-alkylperoxides and iron(III)-acylperoxides \([\text{Fe}^{\text{IV}}\text{OOR}(\text{tpenaH})]^{2+}\) (R = (CH)\(_3\), (CH)\(_2\)Ph, (O)PhCl) form on the replacement of the water equivalent in \([\text{Fe}^{\text{III}}(\text{OH})(\text{tpenaH})]^{2+}\) by ROOH. The complex is bifunctional: The ingoing and outgoing co-ligands are charge separated into a XO\(^-\) (X=H, RO) ligand, and a proton on the non-coordinated pyridinium arm. This system is the first non-heme iron model incorporating a biomimetic second coordination sphere base for enabling this outcome. The \(\nu_{\text{Fe}=\text{O}}\) for the derived \([\text{Fe}^{\text{IV}}=\text{O}(\text{tpenaH})]^{2+}\) is hypsochromically shifted, by around 30 cm\(^{-1}\), compared to the iron(IV)oxo complexes of N-donor only aminopyridyl ligands.\(^{44}\) The way in which these structural and electronic features are important for the indisputable inherent radical character of the unique \([\text{Fe}^{\text{IV}}=\text{O}(\text{tpenaH})]^{2+}\) is yet to be determined, however it is pertinent to note that carboxylato donors are redox non-innocent and this will influence the activation of the bonds to and in cis ligands. For example, the lability of the FeO-OR bond in the alkyl and acyl peroxide adducts of
Fe-tpena is greater than that of analogous iron complexes supported by the more mundane N-donor only ligands. These factors are intrinsic for the unified peroxidase-like mechanism we propose (Scheme 7.3). The speed of the reaction and the extensive characterisation of the iron-based and organic species in our working solutions lead us to propose that the evolved O₂ predominantly derives from the O₂ extrusion from a putative Fe'/OOOR species obtained from coupling of the radical iron(IV)oxo complex with ROO⁻.

With its resting state of +3 oxidation state and a readily accessible +4 oxidation state the iron-tpena system is highly applicable to one-electron reactions in cycles, i.e., those involving HAT reactions as represented by the top section of Scheme 7.1 in the presence of peroxides as terminal oxidants. All the reactions described here support this conclusion. Interestingly, despite the presence of several radical species (ROO⁻, RO⁺, R⁺, [FeIVO(tpena)H]²⁺) in these reactions, with judicial experimental design, the selective oxidation of an external substrate can be favoured.

Ultimately, our results demonstrate that disproportionation of alkyl hydroperoxides and peroxyperacids can potentially be a significant background reaction, when these reagents are used as terminal oxidants in metal-catalysed reactions. It is clear however, given the number of applications of these reagents, including commercial, that significant unproductive decomposition of alkyl hydroperoxide is in fact relatively rare. Finally, as an effective catalyst for alkyl hydroperoxide disproportionation [Fe(tpena)]²⁺ might find useful application in quenching unwanted hydrogen alkyl peroxides in cases of excesses or in chemical spills.

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References


Catalytic Alkyl Hydroperoxide and Acylperoxide Disproportionation by a Nonheme Iron Complex


Chapter 7

(40) by E. Bill (Max-Planck-Institute for Chemical Energy Conversion in Mülheim); available from the author by mail to eckhard.bill@cec.mpg.de. 2016.


(59) The reader should be aware that the coupling reaction of alkylperoxyl radicals, known as the Russell mechanism, was formulated on the basis of experiments involving solutions of alkylhydroperoxides (containing an α-H atom) and their reaction with radical initiators. These solutions do not contain significant amounts of other radicals, like the high valent iron oxo species.


Supporting Information

Supporting video showing the rapid O₂ evolution. In this, two additions of tBuOOH to an acetonitrile solution of [Fe(OH)(tpenaH)]²⁺ (λ_max = 558, [Fe] = 2 mM) and [Fe(OOCumyl)(tpenaH)]²⁺ (λ_max = 531, [Fe] = 4 mM), and their common decay product [FeIV=O(tpenaH)]²⁺ (λ_max = 730) at 5 °C with addition of 50 eq. ROOH.
Figure 7.52: EPR spectrum recorded on a frozen solution of [Fe(tpena)]^{2+} with addition of 50 eq. CumylOOH. Three signals are overlapping assignable to a low-spin iron(III) signal from [Fe(OOCumyl)(tpenaH)]^{2+} \((g = 2.19, 2.12, 1.97)\), a broad low-spin iron(III) signal from fac-[Fe(tpena)]^{2+} \((g = 2.78, 2.32, 1.68)\) and an isotropic peak from the organic radical CumylOO* \((g = 2.00)\).

Figure 7.53: Mössbauer spectrum of a reaction mixture of [Fe(OH)(tpenaH)]^{2+} (3mM) with addition of 50 eq. cumylOOH. [Fe(OH)(tpenaH)]^{2+} \((\delta = 0.14 \text{ mms}^{-1}, \Delta E_Q = 2.08 \text{ mms}^{-1}, 22\%, \text{ blue})\), [Fe_{2}O(tpenaH)]^{4+} \((\delta = 0.43 \text{ mms}^{-1}, \Delta E_Q = 1.60 \text{ mms}^{-1}, 26\%, \text{ red})\), [Fe^{IV}O(tpenaH)]^{2+} \((\delta = 0.00 \text{ mms}^{-1}, \Delta E_Q = 0.90 \text{ mms}^{-1}, 24 \%, \text{ green})\) and [Fe(OOcumyl)(tpenaH)]^{2+} \((\delta = 0.2 \text{ mms}^{-1}, \Delta E_Q = 2.0 \text{ mms}^{-1}, 28\%, \text{ purple})\). The simulations are performed with symmetric Lorentzian doublets due to assumption of fast paramagnetic relaxation, except for [Fe(OOcumyl)(tpenaH)]^{2+}, for which we allowed asymmetric line broadening in order to approximate the broadening effects caused by intermediate relaxation rates.
Figure 7.54: $^{13}$C NMR spectra recorded on a reaction mixture of [Fe(OH)(tpenaH)$_2$]$^{2+}$ (1mM) with addition of 750 eq. $^1$BuOOH after 1 h of reaction time. All of $^1$BuOOH is fully consumed.

Figure 7.55: $^{13}$C NMR spectra recorded on a reaction mixture of [Fe(OH)(tpenaH)$_2$]$^{2+}$ (1 mM) with addition of 750 eq. CumylOOH after 1 h of reaction time. All of CumylOOH is fully consumed.

Figure 7.56: Volumetric detection of O$_2$ release, when various amounts of tBuOOH (70 % aq) were added to 3 mL of 25 μM [Fe(tpena)]$^{2+}$ solution. There is a lack time within the first few seconds after addition.
Figure 7.57: Kinetics for [Fe(tpena)]^{2+} in MeCN with the addition of tBuOOH (664 mM, 457 mM, 348 mM, 236 mM and 164 mM). The rate constants are determined based on the linear relationship between ~20-100 sec. seen in Figure S3. The data can be fitted very well to a linear correlation with Rate constant = $1.07 \times 10^{-2} [\text{tBuOOH}] - 1.26 \times 10^{-3}$; $R^2 = 0.996$.

Figure 7.58: Plot showing the dependency of the rate constant as a function of $[\text{Fe(OH)(tpena)}]^{2+}$ complex concentration.

Figure 7.59: Reference MIMS spectra of methanol (black), acetonitrile (red) and formaldehyde in MeCN (blue). Methanol gives rise to a peak intensity at $m/z = 29, 30$ and $31$, and formaldehyde gives rise to an increase at $m/z = 29$ and $30$. 

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Figure 7.510: $^1$H NMR and $^{13}$C NMR spectra of the reaction mixture of [Fe(OH)(tpenaH)]$^{2+}$ (1 mM, MeCN-d$_3$) and toluene (750 eq.) with subsequent addition of tBuOOH (750 eq.). The spectra are collected after 1 h of reaction time.
Figure 7.5.11: $^{13}$C NMR spectra recorded on a reaction mixture of $\text{[Fe(OH)(tpenaH)]}^{2+}$ with addition of 750 eq. $m$-CPBA after 1 h of reaction time. 50 % of $m$-CPBA has been converted to $m$-CBA (batch: 77 % $m$-CPBA and 23 % $m$-CBA)

Figure 7.5.12: EPR spectrum of $\text{[Fe(tpena)]}^{2+}$ (4 mM) with addition of $m$-chlorobenzoic acid. Microwave frequency: 9.314142 GHz. $g_{\text{eff}}$-values are denoted on the figure