



Nucleophilic reactivity of a mononuclear cobalt(III)–bis(*tert*-butylperoxo) complex†

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A mononuclear cobalt(III)–bis(*tert*-butylperoxo) adduct (Co^{III}–(OO^tBu)₂) bearing a tetraazamacrocyclic ligand was synthesized and characterized using various physicochemical methods, such as X-ray, UV-vis, ESI-MS, EPR, and NMR analyses. The crystal structure of the Co^{III}–(OO^tBu)₂ complex clearly showed that two OO^tBu ligands bound to the equatorial position of the cobalt(III) center. Kinetic studies and product analyses indicate that the Co^{III}–(OO^tBu)₂ intermediate exhibits nucleophilic oxidative reactivity toward external organic substrates.

Transition metal–alkylperoxo (M–OOR) species play an important role in oxidation reactions such as industrial and biological catalytic oxidation.^{1–6} In industrial processes, M–OOR intermediates, such as Co^{III}–OOR complexes, were proposed as key intermediates in hydrocarbon catalytic oxidation under harsh conditions.^{1,7} Mononuclear nonheme M–OOR complexes have been suggested to play a significant role in the oxidation reaction of metalloenzyme systems (*e.g.*, lipoyxygenase and homoprotocatechuate 2,3-dioxygenase).^{8,9} Biomimetic studies of M–OOR complexes enabled catalysts to be developed that produce high value-added organic products under mild conditions.

Mononuclear heme and nonheme first-row M–OOR intermediates (M = Mn, Fe, Co, Ni, and Cu) have been investigated as model complexes for the active sites of metalloenzymes.^{2,5,6,10–13} A number of M–OOR complexes were mainly studied in the investigation of electrophilic reactions (*e.g.*, oxygen and hydrogen atom transfer reaction).^{14–25} It has been reported that the reaction proceeds *via* the •OOR and •OR radicals from decomposition of the M–OOR species.¹ However, only a few examples of nucleophilic reactivity with M–OOR intermediates (M = Fe, Ni, and Cu) have been reported.^{19,20,23}

In the Sharpless–Katsuki epoxidation, Ti–(OOR)_{*n*} (*n* = 1–4) species were proposed as reactive intermediates.^{26,27} Furthermore, in the formation of Fe–OO^tBu complexes, Fe–(OO^tBu)₂ species, [Fe^{III}(TPP)(OO^tBu)₂][–] (TPP = 5,10,15,20-tetraphenylporphyrinate) and [Fe^{III}(BPMCN)(OO^tBu)(HOO^tBu)]²⁺ (BPMCN = *N,N'*-bis(2-pyridylmethyl-*N,N'*-dimethyl-*trans*-1,2-diaminocyclohexane)) adducts, have been proposed as short-lived intermediates.^{28–31} However, definitive evidence of bis(alkylperoxo) binding first-row transition metal compounds has not been reported yet. In this work, we report a fully characterized Co^{III}–(OO^tBu)₂ complex bearing a tetraazamacrocyclic ligand, [Co^{III}(Me₃-TPADP)(OO^tBu)₂]⁺ (**2**, Me₃-TPADP = 3,6,9-trimethyl-3,6,9-triaza-1(2,6)-pyridinacyclodecaphane). Intermediate **2** was investigated in nucleophilic reactions such as aldehyde oxidation. Only one of the two OO^tBu ligands in **2** is able to oxidize external substrates. In order to compare the structure and the reactivity of an alkylperoxo and bis(alkylperoxo) binding cobalt species, Co^{III}–(OO^tBu)(X) complexes, [Co^{III}(Me₃-TPADP)(OO^tBu)(X)]⁺ (X = N₃ for **4**, NCS for **5**), were prepared as well.

The cobalt(II) starting complex, [Co^{II}(Me₃-TPADP)(CH₃CN)₂]²⁺ (**1**), was synthesized by using a published method.³² When 10 equiv. of *tert*-butyl hydroperoxide (^tBuOOH) was added to **1** in the presence of 2 equiv. of triethylamine (TEA) in CH₃CN at 25 °C, the Co^{III}–(OO^tBu)₂ adduct, [Co^{III}(Me₃-TPADP)(OO^tBu)₂]⁺ (**2**), was generated and the solution color changed from purple to dark green (Scheme S1, ESI†). Intermediate **2** is thermally metastable in CH₃CN at 25 °C, which allowed us to use it for characterization and reactivity studies.

The UV-vis spectrum of **2** in CH₃CN at 25 °C shows electronic absorption bands at λ_{max} = ~360 (ε = 1100 M^{–1} cm^{–1}) and 583 nm (ε = 190 M^{–1} cm^{–1}) (Fig. 1a). Electrospray ionization mass spectrometry (ESI-MS) analysis of **2** exhibits a prominent ion peak at *m/z* 485.3, whose mass and isotope distribution pattern correspond to [Co^{III}(Me₃-TPADP)(OO^tBu)₂]⁺ (calcd *m/z* 485.3) (Fig. 1b). The X-band electron paramagnetic resonance (EPR) silence (Fig. 1a, inset) and ¹H NMR spectral features (Fig. S1, ESI†) in the diamagnetic region confirm that complex **2** is a low-spin *S* = 0 cobalt(III) species.

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Fig. 1 (a) UV-vis spectra of $[\text{Co}^{\text{III}}(\text{Me}_3\text{-TPADP})(\text{CH}_3\text{CN})_2]^{2+}$ (**1**) (the black line) and $[\text{Co}^{\text{III}}(\text{Me}_3\text{-TPADP})(\text{OO}^t\text{Bu})_2]^+$ (**2**) (the red line) in CH_3CN at 25°C .³² Inset shows the X-band EPR spectra of **1** (the black line) in frozen CH_3CN at 5 K and **2** (the red line) in frozen CH_3CN at 113 K.³² The parameters for the measurement of **2**: microwave power = 1.0 mW, frequency = 9.176 GHz, sweep width = 0.40 T, and modulation amplitude = 0.60 mT. (b) ESI-MS of **2** in CH_3CN at -40°C . Insets show experimental (upper) and simulated (lower) isotope distribution patterns.

The X-ray crystal structure of $[\text{Co}^{\text{III}}(\text{Me}_3\text{-TPADP})(\text{OO}^t\text{Bu})_2]$ (BPh_4)(Et_2O) ($2\text{-BPh}_4\cdot\text{Et}_2\text{O}$) revealed a distorted octahedral geometry where two *tert*-butyl peroxide ligands coordinate to the cobalt(III) center in the *cis* positions (Fig. 2a). To the best of our knowledge, this is the first crystal structure of a mononuclear $\text{Co}^{\text{III}}\text{-(OO}^t\text{Bu)}_2$ complex. The average Co–O (1.8590 Å) and O–O (1.4757 Å) bond distances of **2** are comparable to those of the $\text{Co}^{\text{III}}\text{-(OO}^t\text{Bu)}$ complexes (Table S2, ESI†).^{1,33}

Thermal decomposition of **2** produced a $\text{Co}^{\text{III}}\text{-(OO}^t\text{Bu)}(\text{OH})$ complex, $[\text{Co}^{\text{III}}(\text{Me}_3\text{-TPADP})(\text{OO}^t\text{Bu})(\text{OH})]^+$ (**3**), in CH_3CN at 25°C (Fig. S2, ESI†).³⁴ Formation of **3** was confirmed by cold spray ionization spectrometry (CSI-MS). The CSI-MS spectrum of **3** shows a prominent signal at m/z 413.17 (calcd m/z 413.20) (Fig. S3, ESI†). Upon adding isotopically labeled H_2^{18}O and D_2O into the solution of **3**, mass peaks at 415.21 and 414.22 corresponding to $[\text{Co}^{\text{III}}(\text{Me}_3\text{-TPADP})(\text{OO}^t\text{Bu})(^{18}\text{OH})]^+$ (calcd m/z 415.20) and $[\text{Co}^{\text{III}}(\text{Me}_3\text{-TPADP})(\text{OO}^t\text{Bu})(\text{OD})]^+$ (calcd m/z 414.20), respectively, were observed (Fig. S3, ESI†, the inset). These mass shifts demonstrate that **3** contains a hydroxide ligand. In a previous study, the $\text{Fe}^{\text{II}}\text{-(OO}^t\text{Bu)}_2$ species was also proposed as a precursor of the $\text{Fe}^{\text{II}}\text{-(OO}^t\text{Bu)}$ species.²⁹ Tajima *et al.* insisted that $[\text{Fe}^{\text{III}}(\text{TPP})(\text{OO}^t\text{Bu})_2]^-$, generated by adding an excess amount of sodium methoxide (NaOCH_3) and $^t\text{BuOOH}$ to the $[\text{Fe}^{\text{III}}(\text{TPP})]^+$ solution, reacted with additional NaOCH_3 , affording the formation of the $[\text{Fe}^{\text{III}}(\text{TPP})(\text{OO}^t\text{Bu})(\text{OCH}_3)]^-$ species.²⁹



Fig. 2 ORTEP plots of the (a) $\text{Co}^{\text{III}}\text{-(OO}^t\text{Bu)}_2$ complex, $[\text{Co}^{\text{III}}(\text{Me}_3\text{-TPADP})(\text{OO}^t\text{Bu})_2]^+$ (**2**), and $\text{Co}^{\text{III}}\text{-(OO}^t\text{Bu)}(\text{X})$ complexes, $[\text{Co}^{\text{III}}(\text{Me}_3\text{-TPADP})(\text{OO}^t\text{Bu})(\text{X})]^+$ ($\text{X} =$ (b) N_3 (**4**), (c) NCS (**5**)), with thermal ellipsoids drawn at the 30% probability level. Hydrogen atoms are omitted for clarity.

We then investigated the electrophilic and nucleophilic reactivities of **2**. The electrophilic reaction of **2** was performed by using styrene and 2,3-dimethyl-2-butene. Upon addition of substrates to the solution of **2** in CH_3CN at 10°C , the intermediate remained intact without showing specific UV-vis spectral changes, and product analysis of these reaction solutions did not show oxidized products (Scheme 1). In contrast, the nucleophilic reactivity of **2** was observed in the oxidation of aldehydes (Scheme 1). Upon the addition of benzaldehyde to **2** in CH_3CN at 15°C , the characteristic absorption band of **2** disappeared with a pseudo-first-order decay (Fig. 3a, the inset and Table S3, ESI†). The product analysis of the reaction solution revealed that benzoic acid (95(1)%) was produced in the oxidation of benzaldehyde (Scheme S2, ESI†). In addition, the cobalt(II)-benzoato complex, $[\text{Co}^{\text{II}}(\text{Me}_3\text{-TPADP})(\text{C}_6\text{H}_5\text{COO})]^+$, was generated after the reaction was completed (Fig. S7, ESI† for CSI-MS analysis). The reactivity of **2** was further investigated with *para*-substituted benzaldehydes, *para*-X-Ph-CHO ($\text{X} = \text{Me, F, Cl, and CF}_3$) (Table S3, ESI†). The Hammett plot of the pseudo-first-order rate constants *versus* σ_p^+ gave a ρ value of 0.7(1) (Fig. 3b). The positive ρ value indicates that **2** has nucleophilic character. The reactivity of **2** was further examined by using primary (1-pentanal for 1°-CHO), secondary (2-methylbutanal for 2°-CHO), and tertiary (pivalaldehyde for 3°-CHO) aldehydes, and the observed reactivity order of $1^\circ\text{-CHO} > 2^\circ\text{-CHO} > 3^\circ\text{-CHO}$ supports the nucleophilic character of **2** as well (Fig. S8, ESI†). Product analyses of the resulting solutions revealed that pentanoic acid (94(3)%), 2-methylbutanoic acid (94(4)%), and 2,2-dimethylpropanoic acid (94(1)%) were produced in the oxidation of 1-pentanal, 2-methylbutanal, and pivalaldehyde, respectively (Table S4, ESI†).

Upon the addition of 2-phenylpropionaldehyde (2-PPA) to **2** in CH_3CN at 25°C under aerobic conditions, the UV-vis absorption



Scheme 1 Overall electrophilic and nucleophilic reactivities of **2**, **4** and **5**.



Fig. 3 Reactions of $[\text{Co}^{\text{III}}(\text{Me}_3\text{-TPADP})(\text{OO}^t\text{Bu})_2]^+$ (**2**) with benzaldehyde in $\text{CH}_3\text{CN}/\text{MeOH}$ ($v/v = 3:1$). (a) UV-vis spectral changes of **2** (0.5 mM) upon addition of 200 equiv. of benzaldehyde at 15 °C. Inset shows the time course of the absorbance at 400 nm. (b) Hammett plot of $\ln k_{\text{rel}}$ against σ_{p}^+ of *para*-substituted benzaldehydes. The k_{rel} values were calculated by dividing k_{obs} of *para*-X-Ph-CHO ($X = \text{Me}, \text{F}, \text{H}, \text{Cl}$, and CF_3) by k_{obs} of benzaldehyde at 15 °C.

band of **2** slightly changed with isosbestic points at 390 and 452 nm, which follows a pseudo-first-order decay profile (Fig. S9, ESI†). The pseudo-first-order rate constants increased proportionally with the 2-PPA concentration, giving a second-order rate constant (k_2) of $4.1(3) \times 10^{-1} \text{ M}^{-1} \text{ s}^{-1}$ at 25 °C (Fig. S10a, ESI†). After the reaction of **2** with 2-PPA, product analysis revealed that acetophenone (95(1)%) was produced as a final product. The CSI-MS spectrum of the reaction solution revealed the formation of **3** and a small amount of cobalt(II)-formate species was also detected under an inert atmosphere (Fig. S11, ESI†). The temperature dependence of the k_2 values was examined in the range of 273–298 K, where a linear Eyring plot was obtained with the activation parameters of $\Delta H^\ddagger = 11(1) \text{ kcal mol}^{-1}$ and $\Delta S^\ddagger = -22(3) \text{ cal mol}^{-1} \text{ K}^{-1}$ (Fig. S10b, ESI†). The observed negative entropy value and the second-order kinetics suggest that the oxidation of 2-PPA by **2** is performed through a bimolecular mechanism.

Interestingly, the same reaction performed under a N_2 atmosphere gives different products. The reaction of **2** with 2-PPA under N_2 in CH_3CN at 25 °C gave a new absorption band at 480 nm (Fig. S12, ESI†). By analysing the resulting solution with CSI-MS, we found that a cobalt(II)-enolate complex, $[\text{Co}^{\text{II}}(\text{Me}_3\text{-TPADP})(\text{OCH}=\text{C}(\text{Me})\text{Ph})]^+$, was formed as a decomposed product (Fig. S13, ESI†). The product analysis of the reaction solution indicated that trace amounts of acetophenone were produced (<1%) after the reaction. When the cobalt(II)-enolate complex was exposed to O_2 , a cobalt(II)-formate complex was obtained as a major product, as observed by CSI-MS (Fig. S14, ESI†). These results are very similar to Tolman's recent mechanism of the aldehyde deformylation pathway *via* a copper(II)-enolate species.³⁵ Based on the kinetic studies and product analyses under N_2 and O_2 , the possible reaction mechanisms for 2-PPA oxidation by **2** are summarized in Scheme 2. The reaction of **2** and 2-PPA in the presence of water afforded enolate and a putative cobalt(III)-(OO^tBu) species through α -deprotonation of 2-PPA by one of the alkylperoxides of **2**. The putative cobalt(III)-(OO^tBu) species decomposed to the cobalt(II)-enolate complex under N_2 . In the presence of O_2 , the enolate is oxidized to acetophenone, and complex **3** is produced as a final product.

In the aldehyde oxidation, only one OO^tBu ligand in **2** was able to participate in the oxidation of 2-PPA (Scheme 1). To compare the reactivity properties of $\text{Co}^{\text{III}}(\text{OO}^t\text{Bu})$ and $\text{Co}^{\text{III}}(\text{OO}^t\text{Bu})_2$ complexes, $\text{Co}^{\text{III}}(\text{OO}^t\text{Bu})(\text{X})$ complexes, $[\text{Co}^{\text{III}}(\text{Me}_3\text{-TPADP})(\text{OO}^t\text{Bu})(\text{X})]^+$ ($X = \text{N}_3$ for **4**, NCS for **5**), were synthesized. **4** and **5** were prepared by adding 1.1 equiv. of NaX ($X = \text{N}_3$, NCS) to the reaction solution of **1** in CH_3CN at 25 °C and then 5 equiv.



Scheme 2 Proposed reaction pathways of **2** with 2-PPA under N_2 and O_2 ($L = \text{Me}_3\text{-TPADP}$, $R = ^t\text{Bu}$).

of t -BuOOH and 2 equiv. of TEA were added (Scheme S1, ESI[†]). Characterization of **4** and **5** was performed by UV-vis, ESI-MS, EPR, and ^1H NMR analyses (Experimental section and Fig. S15–S19, ESI[†]).

The single crystals of **4** and **5** revealed a similar distorted octahedral geometry to that of **2** in which one OO^tBu ligand bound to the cobalt(III) center was located in the *trans* position of the amine group and the other anionic monodentate ligand, X, was located in the *trans* position of the pyridine ring (Fig. 2b and c). These data clearly indicate that the OO^tBu ligand in the *trans* position of the pyridine ring in **2** was substituted with an anionic ligand in **3** and **4**. The Co–O1 bond distances (1.862(3) Å for **4**, 1.880(4) Å for **5**) and O1–O2 bond distances (1.479(4) Å for **4**, 1.430(6) Å for **5**) were within the range of those of the reported $\text{Co}^{\text{III}}\text{--OO}^t\text{Bu}$ complexes and similar to those of **2** (Table S2, ESI[†]).^{1,33}

In the reactions of **4** and **5** with 2-PPA, we could not observe any change in the UV-vis spectra. Based on the reactivity and structural comparison of **2**, **4**, and **5**, the reaction site of **2** is presumed to be the OO^tBu ligand in the *trans* position of the pyridine ring. Further theoretical calculations on the detailed reaction mechanism of **2** with substrates are underway and will clarify the reaction site of **2**.

In conclusion, we have synthesized and characterized a mononuclear $\text{Co}^{\text{III}}\text{--}(\text{OO}^t\text{Bu})_2$ intermediate, $[\text{Co}^{\text{III}}(\text{Me}_3\text{TPADP})(\text{OO}^t\text{Bu})_2]^+$ (**2**), with various physicochemical methods including UV-vis, ESI-MS, EPR, X-ray, and NMR analyses. In the kinetic studies, under mild conditions, one of the two OO^tBu ligands in **2** is capable of performing a nucleophilic reaction (*i.e.*, aldehyde oxidation). A $\text{Co}^{\text{III}}\text{--}(\text{OO}^t\text{Bu})(\text{OH})$ complex, **3**, was generated by thermal decomposition of **2** and/or deformylation reaction of 2-PPA by **2** in the presence of O_2 . Furthermore, $\text{Co}^{\text{III}}\text{--}(\text{OO}^t\text{Bu})$ complexes, $[\text{Co}^{\text{III}}(\text{Me}_3\text{TPADP})(\text{OO}^t\text{Bu})(\text{X})]^+$ (X = N_3 for **4**, NCS for **5**), which have a OO^tBu ligand in the *trans* position of the amine group were prepared, and **4** and **5** did not undergo aldehyde oxidation.

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Conflicts of interest

The authors declare no competing financial interest.

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