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Steric Control and Mechanism of Benzaldehyde Oxidation by Polypyridyl Oxoiron(IV) Complexes: Aromatic versus Benzylic Hydroxylation of Aromatic Aldehydes

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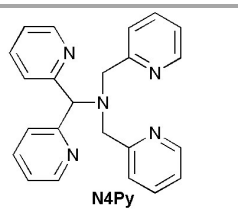
Abstract: The present study describes the first example of the hydroxylation of benzaldehydes by synthetic nonheme oxoiron(IV) complexes, where the reactivity, chemoselectivity, and mechanism was strongly influenced by the ligand enviroment of the iron center.

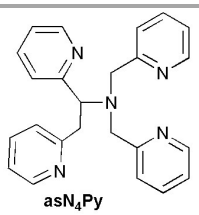
Pterin-dependent hydroxylases, including phenylalanine (PheH), tyrosine (TyrH), and tryptophan (TrpH) hydroxylase are non-heme mononuclear iron enzymes with 2-His-1-carboxylate platform,[1] which are responsible for essential biological functions such as biosynthesis of tyrosine (PheH), and various neurotransmitters like dopamine, norepinephrine, epinephrine (TyrH), and serotonin (TrpH).[2] For such enzymes, catalytic oxoiron(IV) intermediates have been postulated to introduce a hydroxyl group on the aromatic ring via their electrophilic attack on the aromatic ring supported by inverse KIE and a NIH shift.[3] High-valent oxoiron complexes are also present as the reactive intermediates for the oxidative catalysis by α-ketoglutarate dependent non-heme iron-containing oxygenases, which can perform hydroxylation of aliphatic C-H bonds on various substrates.[4] In this case the key step is the hydrogen atom abstraction from the substrate by oxoiron(IV) species resulting in the caged radical pair [Fe(III)-OH-$^{\cdot}$R] followed by the formation of R-OH via oxygen rebound pathway based on the large *KIE* values of ~50 for taurin: α-KG dioxygenase[4b,d] and ~60 for prolyl-4-hydroxylase[4e]. Synthetic model systems[5] including mononuclear nonheme oxoiron(IV) intermediates may play a key role to get more insight into the mechanism of action in these enzymes.

As a functional models of pterin-dependent hydroxylases a stoichiometric hydroxylation of aromatic compounds such as pendant aromatic ring on the ligand [Fe^{II}(6-PhTPA)/PhIO;[6] Fe^{II}(6-PhTPA)/^{t}BuOOH) (6-PhTPA = bis(2-pyridylmethyl)-6-phenyl-2-pyridylmethylamine),[7] benzoic acid (Fe^{II}(BPMEN)/BA/H_2O_2),[8] and *m*-chloroperbenzoic acid (Fe^{II}(TPA)/*m*-CPBA;[9] Fe^{II}(BPMEN)/*m*-CPBA[8], where BPMEN = *N*,*N*'-dimethyl-*N*,*N*'-bis(2-pyridylmethyl)ethane-1,2-diamine, and TPA = tris(2-pyridylmethyl)amine) by nonheme iron complexes with two *cis*-labile sites have been described in detail. Based on their observations oxoiron(IV) and/or oxoiron(V) via the formation of a (κ^2-acylperoxo)iron(III) species have been proposed as key intermediates for the aromatic hydroxylation.[7-9] Benzaldehydes may serve as good candidates to probe biologically relevant C-H hydroxylation, and to study the mechanism of the hydrogen atom abstraction and the formation of the concomitant product from the caged radical pair. Only few examples can be found in the literature, where high-valent oxometal complexes are directly involved in the benzaldehyde oxidation.[10] The kinetics and mechanisms of the oxidation of aromatic aldehydes to carboxylic acids, by cis-$[Ru^{IV}(bpy)_2(py)(O)]^{2+}$ and $[Ru^{IV}(tpy)(bpy)(O)]^{2+}$ (bpy = 2,2'-bipyridine, py = pyridine, and tpy = 2,2':6',2"-terpyridine) in water and acetonitrile have been extensively studied.[10b] Oxoiron(IV) complex supported by pentadentate N4Py (N4Py = *N*,*N*'-bis(2-pyridylmethyl)-*N*-bis(2-pyridyl)methylamine) ligand has been reported to oxidize various substrates by a high variety of mechanisms, including electron transfer (ET),[11a] electron transfer-proton transfer (ET-PT),[11b] hydrogen atom abstraction (HAT),[11c,d] and oxygen atom transfer (OAT).[11e,f]

Herein, we present the comparison of the stoichiometric oxidation of benzaldehyde to benzoic acid and/or salicylic acid by previously characterized (UV-vis, ESI-MS, Mössbauer…) $[Fe^{IV}(N4Py)(O)]^{2+}$,[12a] (**2**) and $[Fe^{IV}(asN4Py)(O)]^{2+}$,[12b] (**4**) (asN4Py = *N*,*N*-bis(2-pyridylmethyl)-1,2-di(2-pyridyl)ethylamine)(Fig. 1).



$[Fe^{II}(N4Py)(CH_3CN)](ClO_4)_2$ (**1**)
$[Fe^{IV}(N4Py)(O)](ClO_4)_2$ (**2**)



$[Fe^{II}(asN4Py)(CH_3CN)](ClO_4)_2$ (**3**)
$[Fe^{IV}(asN4Py)(O)](ClO_4)_2$ (**4**)

Fig. 1. Iron(II) and iron(IV) complexes used in this study.

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Interestingly, the aromatic hydroxylation does not occur in the reaction of **2** but does with **4**, which may be explained by the replacement of one of the pyridyl moiety by a more labile 2-pyridylmethyl arm on the N4Py ligand.

The oxidation potential of **2** has been studied at 25°C in a HAT processes with *p*-substituted benzaldehydes. The oxidation reactions were carried out anaerobically at room temperature in dry acetonitrile. Organic products were characterized by GC/MS and quantitated using naphthalene as an internal standard. Complex **2** was generated by the reaction of **1** with 2 equiv. of PhIO (<40 min), and the rate of its rapid decomposition, which coincided with the regeneration of **1** (λ_{max} = 380 and 449 nm), was measured as a function of the concentration of added PhCHO. The yield of benzoic acid was almost quantitative (~90%), indicating that the UV-vis spectral change corresponds to the HAT process. An isobestic point was observed at 560 nm, indicating that there were no long-lived intermediates in the conversion of the green species into the Fe^{II} product. Furthermore, no shifts have been observed in the λ_{max} value of **2** after the addition of PhCHO, excluding any complexation with the oxidant (Fig. 2a). The spectral changes observed for the reactions between the various benzaldehyde derivatives and **2** are virtually identical. The rates in the presence of a large excess of PhCHO (130-330 equiv.) obeyed pseudo-first order kinetics, and the pseudo-first order rate constants increased proportionally with the substrate concentration (Fig. 2b, Table S1, ESI†). From this linear plotting, the second order rate constant (k_2) was determined to be 8.17×10^{-2} M^{-1} s^{-1} at 25°C, which is comparable to that measured in oxidation of benzyl alcohol (9.9×10^{-2} M^{-1} s^{-1})[11d] by **2**. Similar values were observed under air and in the presence of 5 equivalent of benzyl alcohol as inhibitor (8.36×10^{-2} and 8.29×10^{-2} M^{-1} s^{-1}, respevtively), excluding the involvement of the dioxygen (autoxidation of benzaldehyde) in the rate-determining step. This value is much smaller than those obtained for the oxidation of PhCHO by *cis*-$[Ru^{IV}(bpy)_2(py)(O)]^{2+}$ and $[Ru^{IV}(tpy)(bpy)(O)]^{2+}$ complexes (1.05 and 3.67 M^{-1} s^{-1} at 25°C, respectively).[10b] Finally, activation parameters of $\Delta H^{\neq}$ = 20.5 kJ mol^{-1} and $\Delta S^{\neq}$ = -276 J mol^{-1} K^{-1} were calculated from plots of ln(k/T) versus 1/T in CH_3CN over the temperature range 278 to 303 K for the oxidation of PhCHO (Fig. S1-S2, ESI†)). Activation parameters obtained for *cis*-$[Ru^{IV}(bpy)_2(py)(O)]^{2+}$ and $[Ru^{IV}(tpy)(bpy)(O)]^{2+}$ were $\Delta H^{\neq}$ = 45 kJ mol^{-1}, $\Delta S^{\neq}$ = -96 J mol^{-1} K^{-1}, and $\Delta H^{\neq}$ = 20 kJ mol^{-1}, $\Delta S^{\neq}$ = -168 J mol^{-1} K^{-1}, respectively.[10b] The large negative activation entropies are typical of associative processes, and indicate that the transition state is better organized than the prior step.

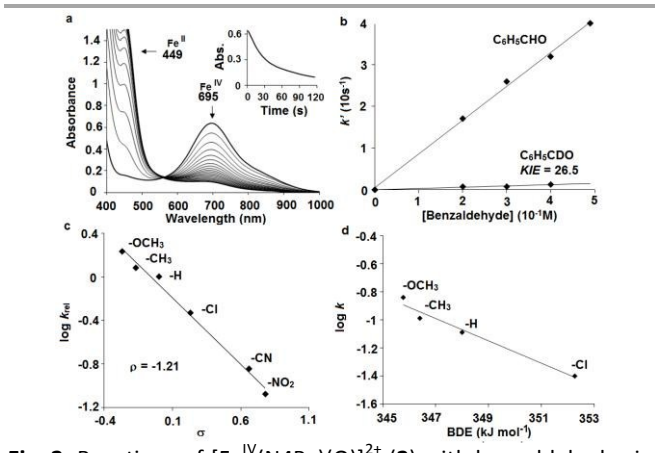


Fig. 2. Reactions of $[Fe^{IV}(N4Py)(O)]^{2+}$ (**2**) with benzaldehydes in CH_3CN at 298 K. (a) UV-vis spectral change of **2** (1.5 mM) upon addition of 267 equiv. PhCHO. Inset shows time course of the decay of **2** monitored at 695 nm. (b) Plot of *k'* versus [substrate] for reactions of **2** (1.5 mM) with PhCHO, and PhCDO. (c) Hammett plot of log k_{rel} against σ_p of *para*-substituted benzaldehydes. (d) The logk_2 versus BDE_{C-H} plots.

Competitive reactions were done with *para*-substituted benzaldehyde derivatives in order to evaluate the influence of electronic factors on the reaction (Fig. 2c, Table S2, ESI†). The relative reactivity shows linear correlation (r = 0.99, n = 6) with Hammett's σ constant. The reaction constant, ρ, is negative (ρ = −1.21), demonstrating that the rate constant for oxidation of the benzaldehydes by **2** is sensitive to changes in the electronic properties of the aldehyde; electron-donating groups on the substrate increases and electron-withdrawing groups decreases the reaction rate. This result suggests that the metal-based oxidant is electrophilic, where the oxidation of benzaldehydes mediated by complex **2** proceeds through polar transition states with charge transfer from the substrate to the iron. The relatively small ρ value suggests that there is a small development of positive charge on the substrate in the transition state. Comparison with literature ρ values for related ET and direct HAT processes suggests that the benzylic (aldehydic) oxidation by the oxoiron(IV) intermediate occurs by the latter mechanism rather than reaction of the oxo species with the aromatic ring, where a more negative ρ value would be expected. This value is also considerably less than ρ = -3.0 for the oxidative *N*-dealkylation reaction of anilines by **2** in a mechanism that has been described as electron-proton transfer (ET-PT).[11b] The Hammett ρ value is twofold larger than that observed in the closely related *cis*-$[Ru^{IV}(bpy)_2(py)(O)]^{2+}$/PhCHO ($\rho$ = -0.65) system.[10b] Furthermore, threefold larger than those obtained for the oxoiron(IV)(porphyrin radical cation)/$PhCH_2OH$ (ρ = -0.4),[13] and 17-fold larger than those obtained for *bona fide* nonheme oxoiron(IV)/$PhCH_2OH$ systems (ρ = -0.07),[13] so the oxidation of benzaldehydes is much more sensitive to electronic effects than the benzyl alcohol oxidation was.

Substrate PhCHO/PhCDO kinetic isotope effect (*KIE*) was also investigated (Fig. 2b, Table S3, ESI†). The involvement of the aldehydic C-H bond is indicated by the magnitude of the k_{CH}/k_{CD} kinetic isotope effects of 26.5. This value is larger than "classical" *KIE* values (*KIE* ~7) and those measured in the oxidation of PhCHO by *cis*-$[Ru^{IV}(bpy)_2(py)(O)]^{2+}$ and $[Ru^{IV}(tpy)(bpy)(O)]^{2+}$ complexes (*KIE* ~8 and ~6, respectively),[10b] lower than that observed for the oxidation of benzyl alcohol (*KIE* of ~50),[11d] but comparable to that measured in the oxidation of series of alkanes (*KIE* ~20)[11c] by **2**. Based on literature data above, such a large *KIE* value indicates that nonheme oxoiron(IV) intermediate activates benzaldehyde by an H-atom abstraction from the aldehydic C-

H of benzaldehyde via a tunneling-like HAT mechanism, and that this C-H bond cleavage is the rate-determining step.[15] Very large *KIE*s were also found in the HAT for different nonheme iron enzymes, which shows that the C-H bond cleavage is the rate-determining step, and hydrogen tunneling plays an important role in these reactions.[4b,d] Homolytic bond dissociation energies (BDEs) are known for a variety of substrates including C-H bond. A good linear correlation exists between logk_2 and C-H BDE for several of the aldehydes studied here (Fig. 2d). It has a slope of -0.33, which is twofold larger than the slope for the oxidation of alkanes by complex **2** (-0.18).[11c] Similar correlations have been observed in C-H bond oxidations by mononuclear nonheme oxoiron(IV) species with a mechanism that involves rate-determining HAT.[16]

Similarly to the **2**/PhCHO system, the reactivity of $Fe^{IV}(O)(asN4Py)](ClO_4)_2$ (**4**) has been also studied at 25°C in the oxidation reaction of PhCHO and several of its derivatives. The oxidation reactions were carried out anaerobically at room temperature in dry acetonitrile. Organic products, derived from the hydrolyzed complexes, were characterized by GC/MS (ESI†). Complex **4** was generated by the reaction of **3** with 2 equiv. of PhIO (<40 min), and the rate of its rapid decomposition at 705 nm, and the formation of a new purple species (**5**) with a λ_{max} at 568 nm were measured as a function of the concentration of added PhCHO (Fig. 3a, Table S4, ESI†). An isobestic point was observed at ~675 nm, indicating that there were no long-lived intermediates in the conversion of the green species into the new purple species. UV/VIS spectra of the stable endpoint chromophores was identical to that of the independently synthesized iron(III) salicylate complex, $[Fe^{III}(asN4Py)(O_2C(C_6H_4)O)](ClO_4)$, with a characteristic ligand-to-metal charge-transfer (LMCT) band at 568 nm (ε ~2000 M^{-1} cm^{-1}) (Fig. S3, ESI†). No reaction has been observed by the use of benzoic acid as a possible candidate, but similar species has been formed in the reaction of **3** with *m*-CPBA (λ_{max} at 560 nm), and almost identical spectral features were observed for Fe^{III}(TPA) and Fe^{III}(BPMEN) salicylate complexes.[8,9] The maximum formation of **3** and **5** was determined to be ~50-50% in the presence of a large excess of PhCHO by comparing the intensities of absorption bands at 409 and 568 nm with the known ε values of **3**,[12b] and the independently prepared **5** complexes (Fig. S3, ESI†).

Competitive reactions were also done with *para*-substituted benzaldehyde derivatives, and the observed characteristic LMCT bands (λ_{max}^{-1}) show linear correlation with Hammet's σ constants (Fig. S4, ESI†). The rates in the presence of a large excess of PhCHO (133-367 equiv.) showed pseudo-first order kinetics, and the pseudo-first order rate constants increased proportionally with the substrate concentration (Fig. 3b). From this linear plotting, the second order rate constant (k_2) was determined to be 2.19 × 10^{-2} M^{-1} s^{-1} at 25°C, which is comparable to that measured in oxidation of benzyl alcohol (1.25 × 10^{-2} M^{-1} s^{-1}) under same conditions, but 4-fold smaller than that observed in oxidation of benzaldehyde (8.17 × 10^{-2} M^{-1} s^{-1}) by **2**. Similar values were observed under air and dioxygen (2.27 × 10^{-2} and 2.34 × 10^{-2} M^{-1} s^{-1}, respevtively), excluding the involvement of the dioxygen (autoxidation of

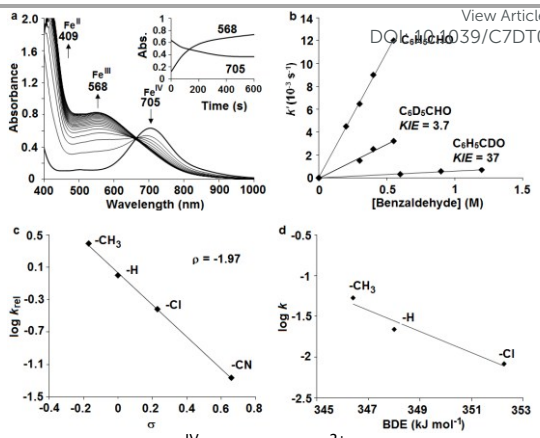


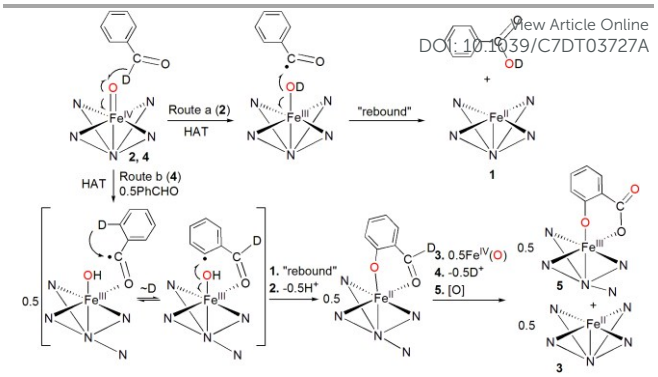
Fig. 3. Reactions of $[Fe^{IV}(asN4Py)(O)]^{2+}$ (**4**) with benzaldehydes in CH_3CN at 298 K. (a) UV-vis spectral change of **4** (1.5 mM) upon addition of 267 equiv. PhCHO. Inset shows time course of the decay of **4**, and the formation of **5** monitored at 705 and 568 nm. (b) Plot of *k*' versus [substrate] for reactions of **2** (1.5 mM) with PhCHO, and PhCDO. (c) Hammett plot of log k_{rel} against σ_p of *para*-substituted benzaldehydes. (d) The logk_2 versus BDE_{C-H} plots.

benzaldehyde) in the rate-determining step. Finally, activation parameters of $\Delta H^{\neq}$ = 32 kJ mol^{-1} and $\Delta S^{\neq}$ = -284 J mol^{-1} K^{-1} were calculated from plots of ln(*k*/T) versus 1/T in CH_3CN over the temperature range 278 to 303 K for the oxidation of PhCHO (Fig. S5-S6, ESI†). The large negative activation entropies are typical of associative processes, and indicate that the transition state is better organized than the prior step. To get insight into the mechanism of the **4**-mediated oxidation, we have investigated the effect of the substituent in the *para*-position of benzaldehyde, and the observed kinetic data were treated in terms of the Hammett equation (Table S5, ESI†). The Hammett plot in Fig. 3c shows that a correlation exists between logk_{rel} and σ with a slope of ρ = -1.97. The correlation demonstrates that the rate constant for oxidation of the benzaldehydes by **4** is also sensitive to changes in the electronic properties of the aldehyde, with electron-donating substituents increasing reactivity and electron-attracting groups decreasing it. The magnitude of the ρ value is in a good agreement with a hydrogen-atom-transfer (HAT) model. Its value is significantly larger than those observed for the **2**/PhCHO and $Ru^{IV}O$/PhCHO systems above, but considerably smaller than what is expected for the ET-PT reaction (ρ ~3.0),[11b] and for the direct oxidation of the aromatic ring (ρ ~-3.9).[11a]

Substrate C_6H_5CHO/C_6H_5CDO and C_6H_5CHO/C_6D_5CHO kinetic isotope effects (KIEs) were also investigated (Table S5-S6, ESI†). As shown in Fig. 3b benzaldehyde oxidation can be associated with two *KIE*s: ~37 for deuteration of the aldehydic group and 3.7 for deuteration of the aromatic ring. Furthermore, there is a clear correlation between the rate constant for H-atom abstraction and the C-H bond dissociation energy (BDE) of the aldehydes studied here (Fig. 3d). It has a slope of -0.50, which is significantly larger than the slope for the oxidation of alkanes by complex **2** (-0.18). This correlation together with the large deuterium isotope effect for the

oxidation of C_6H_5CHO/C_6H_5CDO indicates that the aldehydic C-H bond breaking is important part of the rate-limiting step, and the reaction of **4** proceeds by H-atom transfer via tunneling-like mechanism. In contrast to the PhCHO oxidation, a large Hammett ρ value of -3.9, and inverse *KIE* = k_H/k_D value of ~0.9 were calculated for the aromatic ring oxidation by complex **2**, involving an initial electrophilic attack on the π-system of the aromatic ring resulting in a tetrahedral radical or cationic σ-complex, instead of HAT mechanism. Fractional 1,2 hydrogen shifts ("NIH shifts") have also been suggested for the intramolecular iron(IV)-mediated aromatic substitution reaction including oxene and nitrene transfer reactions.[6] Based on these results above, the observed C_6H_5CHO/C_6D_5CHO *KIE* of 3.7 may be explained by intramolecular hydrogen shift between the aromatic and benzylic positions after the HAT process but still in the rate-determining step before the OH rebound.

In summary, both the benzylic and arene oxidation can be drawn with the two different tautomers of the intermediate benzoyl radical as shown in Scheme 1. Since the redox properties of **1** and **3** complexes are almost identical ($E_{1/2}$ = 1.01 V and 0.95 V vs. SCE, respectively), the difference in the mechanisms can be explained by different geometries around the iron centers. Similarly to the recently published results, the aromatic ring oxidation occurs only in the presence of **4**, which has two *cis*-labile sites for the formation of a six-membered-ring transition state. The benzylic oxidation by **2** and **4** can be drawn by an intermolecular tunneling-like HAT processes in both cases. In summary, we can conclude that the replacement of a pyridyl arm with a 2-pyridylethyl arm can significantly affect the chemoselectivity of the oxoiron(IV) species in hydroxylation reactions of benzaldehydes.



Sceme 1. Proposed mechanisms for benzylic (Route a) and aromatic (Route b) hydroxylation by oxoiron(IV) complexes.

Notes and references

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1 (a) O. A. Andersen, A. J. Stokka, T. Flatmark, E. Hough, *J. Mol. Biol.*, 2003, **333**, 747-757; (b) L. Wang, H. Erlandsen, J. Haavik, P. M. Knappskog, R. C. Stevens, *Biochemistry*, 2002, **41**, 12569-12574; (c) K. E. Goodwill, C. Sabatier, R. C. Stevens, *Biochemistry*, 1998, 37, 13437-13445.

2 (a) E. G. Kovaleva, J. D. Lipscomb, *Nat. Chem. Biol.*, 2008, **4**, 186-193; (b) M. Costas, M. P. Mehn, M. P. Jensen, L. Que, Jr., *Chem. Rev.*, 2004, **104**, 939-986; (c)M. M. Abu-Omar, A. Loaiza, N. Hontzeas, *Chem. Rev.*, 2005, **105**, 2227-2252; (c) P. C. A. Bruijnincx, G. van Koten, R. J. M. Klein Gebbink, *Chem. Soc. Rev.*, 2008, **37**, 2716-2744; (d) P. F. Fitzpatrick, *Annu. Rev. Biochem.*, 1999, **68**, 355-381.

3 (a) A. J. Panay, M. Lee, C. Krebs, J. M. Bollinger, P. F. Fitzpatrick, *Biochemistry*, 2011, **50**, 1928-1933; (b) B. E. Eser, E. W. Barr, P. A. Frantom, L. Saleh, J. M. Bollinger, C. Krebs, P. F. Fitzpatrick, *J. Am. Chem. Soc.*, 2007, 129, 11334-11335; (c) K. M. Roberts, J. A. Pavon, P. F. Fitzpatrick, *Biochemistry*, 2013, 52, 1062-1073; (d) J. A. Pavon, B. Eser, M. T. Huynh, P. F. Fitzpatrick, *Biochemistry*, 2010, **49**, 7563-7571; (d) J. A. Pavon, P. F. Fitzpatrick, *J. Am. Chem. Soc.*, 2009, **131**, 4582-4583; (e) S. Martinez, R. P. Hausinger, *Biochemistry*, 2016, **55**, 5989-5999.

4 (a) J. C. Price, E. W. Barr, B. Tirupati, J. M. Bollinger, C. Krebs, *Biochemistry*, 2003, **42**, 7497-7508; (b) Sinnecker, N. Svensen, E. W. Barr, S. Ye, J. M. Bollinger, F. Neese, C. Krebs, *J. Am. Chem. Soc.*, 2007, **129**, 6168-6179; (c) D. A. Proshlyakov, T. F. Henshaw, G. R. Monterosso, M. J. Ryle, R. P. Hausinger, *J. Am. Chem. Soc.*, 2004, **126**, 1022-1023; (d) J. C. Price, E. W. Barr, T. E. Glass, C. Krebs, J. M. Bollinger, *J. Am. Chem. Soc.*, 2003, **125**, 13008-13009; (e) L. M. Hoffart, E. W. Barr, R. B. Guyer, J. M. Bollinger, C. Krebs, *Proc. Natl. Acad. Sci.*, 2006, **103**, 14738-14743.

5 (a) A. R. McDonald, L. Que, Jr., *Coord, Chem. Rev.*, 2013, **257**, 414-428; (b) L. Que, Jr., *Acc. Chem. Res.*, 2007, **40**, 493-500; (c) W. Nam, *Acc. Chem. Res*., 2007, **40**, 465-465.

6 M. P. Jensen, M. P. Mehn, L. Que, Jr., *Angew. Chem. Int. Ed.*, 2003, **42**, 4357-4360.

7 M. P. Jensen, S. J. Lange, M. P. Mehn, E. L. Que, L. Que, Jr., *J. Am. Chem. Soc.*, 2003, **125**, 322.

8 S. Taktak, M. Flook, B. M. Foxman, L. Que, Jr., E. V. Rybak-Akimova, *Chem. Commun.*, 2005, 5301-5303.

9 N. Y. Oh, M. S. Seo, M. H. Lim, M. B. Consugar, M. J. Park, J.-U. Rohde, J. Han, K. M. Kim, J. Kim, L. Que, Jr., W. Nam, *Chem. Commun.*, 2005, 5644-5646.

10 (a) G. Green, W. Griffith, D. H. Hollinshead, S. V. Ley, M. Schroder, *J. Chem. Soc., Perkin Trans. 1*, 1984, 681-686; (b) W. K. Seok, T. J. Meyer, *Inorg. Chem.*, 2005, **44**, 3931-3941.

11 (a) S. P. de Visser, K. Oh, A.-R. Han, W. Nam, *Inorg. Chem.*, 2007, **46**, 4632-4641; (b) K. Nehru, M. S. Seo, J. Kim, W. Nam, *Inorg. Chem.*, 2007, **46**, 293-298; (c) J. Kaizer, E. J. Klinker, N. Y. Oh, J. U. Rohde, W. J. Song, A. Stubna, J. Kim, E. Munck, W. Nam and L. Que Jr., *J. Am. Chem. Soc.,* 2004, **126**, 472; (d) N. Y. Oh, Y. Suh, M. J. Park, M. S. Seo, J. Kim, W. Nam, *Angew. Chem. Int. Ed.*, 2005, **44**, 4235-4239; (e) C. V. Sastri, M. S. Seo, M. J. Park, K. M. Kim, W. Nam, *Chem. Commun.*, 2005, 1405-1407; (f) D. Lakk-Bogáth, G. Speier, J. Kaizer, *New J. Chem.,* 2015, **39**, 8245.

12 (a) E. J. Klinker, J. Kaizer, W. W. Brennessel, N. L. Woodrum, C. J. Cramer and L. Que Jr., *Angew. Chem. Int. Ed.,* 2005, **44**, 3690-3694; (b) D. Lakk-Bogath, R. Csonka, G. Speier, M. Reglier, A. J. Simaan, J. V. Naubron, M. Giorgi, K. Lazar, J. Kaizer, *Inorg. Chem.*, 2016, **55**, 10090-10093.

13 N. Y. Oh, Y. Suh, M. J. Park, M. S. Seo, J. Kim, W. Nam, *Angew. Chem. Int. Ed.,* 2005*,* **44**, 4235-4239.

14 S. P. de Visser, K. Oh, A.-R. Han, W. Nam, *Inorg. Chem.*, 2007, **46**, 4632-4641.

15 E. J. Klinker, S. Shaik, H. Hirao, L. Que, Jr., *Angew. Chem. Int. Ed.*, 2009, **48**, 1291-1295.

16 M. Mitra, H. Nimir, S. Demeshko, S. S. Bhat, S. O. Malinkin, M. Haukka, J. Lloret-Fillol, G. C. Lisensky, F. Meyer, A. A. Shteinman, W. R. Browne, D. A. Hrovat, M. G. Richmond, M. Costas and E. Nordlander, *Inorg. Chem.,* 2015, **54**, 7152-7164.

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Steric Control and Mechanism of Benzaldehyde Oxidation by Polypyridyl Oxoiron(IV) Complexes: Aromatic versus Benzylic Hydroxylation of Aromatic Aldehydes

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Stoichiometric oxidation of benzaldehyde to benzoic acid or salicylic acid by $[Fe^{IV}(N4Py)(O)]^{2+}$ and $[Fe^{IV}(asN4Py)(O)]^{2+}$ complexes have been carried out.