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Synthesis, Structural Characterization, and Extradiol Oxygenation of Iron−Catecholato Complexes with Hydrotris(pyrazolyl)borate Ligands[†,‡]

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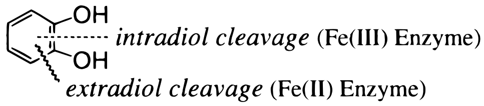
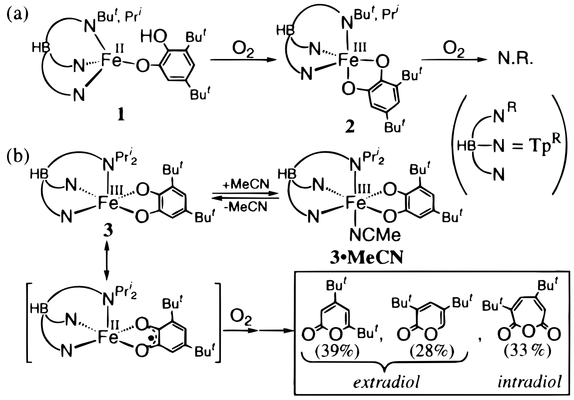
Many iron−catecholato complexes have been investigated to get insights into chemical and structural features of catechol dioxygenases which catalyze the oxidative cleavage of catechol ring (Chart 1).[1−4] However, most of the previous catechol dioxygenase models are octahedral Fe(III) complexes with tetradentate ligands.[5−7] The Fe(III) catecholato complex with the TACN (=1,4,7-triazacyclononane) ligand is the only known example of a complex with a tridentate ligand, and it is notable that the reaction of this catecholato complex with O_2 results in extradiol ring cleavage.[8] We have been investigating Fe complexes with the trigonally capping hydrotris(pyrazolyl)borate ligands (=Tp^R; R denotes substituents of the 3- and 5-positions of pyrazolyl rings), which can mimic the coordination environment made by three histidyl residues often found in metalloproteins.[9] Because the hindered Tp^R ligands can stabilize coordinatively unsaturated (i.e., 4- or 5-coordinated) iron centers,[9,10] Tp^RFe−catecholato complexes should show unique structural and chemical properties. In this paper, we report the structural characterization and the reactivity toward O_2 of coordinatively unsaturated ferrous and ferric catecholato complexes with the Tp^R ligands (R = Bu^t,Pr^i and Pr^i_2). We have found that O_2 treatment of the $Tp^{Pr^i_2}$ complex results in *extradiol* cleavage, for which a vacant coordination site for O_2 is essential.

Chart 1



Scheme 1



At first, the highly sterically hindered Tp^{Bu^t,Pr^i} was adopted to isolate mononuclear Fe complexes. Reaction of an Fe(II)−catecholato complex, $Tp^{Bu^t,Pr^i}Fe^{II}$(DBCH) (**1**),[11,12] with O_2 afforded the corresponding Fe(III)−catecholato complex, $Tp^{Bu^t,Pr^i}Fe^{III}$(DBC) (**2**), but neither extra- nor intradiol cleavage occurred (Scheme 1 a). A UV−vis spectrum of **2** (toluene solution) showed broad intense absorptions at 672 and 830 nm which were assigned as catecholate-to-Fe(III) charge-transfer bands.[13] However, the pattern of the spectrum was slightly different from those of the previously reported 6-coordinate Fe(III)-DBC complexes; the higher energy band of **2** was red-shifted compared to those of the 6-coordinate complexes.[5,6,12] X-ray crystallographic analysis (Figure 1) has revealed that the geometry of the Fe(III) center is a 5-coordinate trigonal bipyramid with the trigonal basal plane defined by the two pyrazolyl nitrogen atoms (N21 and N21′) and one oxygen atom from DBC (O2). The C−O bond lengths of the catecholate moiety (1.35(2) and 1.38(2) Å) are longer than those in the chelating semiquinonate (1.265−1.301 Å),[14,15] indicating that **2** is not an Fe(II)−semiquinonato complex but an Fe(III)−catecholato complex. This coordination environment

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[†] This paper is dedicated to the authors' former supervisor and co-worker, Nobumasa Kitajima (deceased Jan 8, 1995).

[‡] Abbreviations used in this paper: Tp^{Bu^t,Pr^i}, hydrotris(3-*tert*-butyl-5-*iso*-propyl-1-pyrazolyl)borate; $Tp^{Pr^i_2}$, hydrotris(3,5-di-*iso*-propyl-1-pyrazolyl)borate; $DBCH_2$, 3,5-di-*tert*-butylcatechol; TACN, 1,4,7-triazacyclononane; 6TLA, tris[(6-methyl-2-pyridyl)methyl]amine.

(1) (a) Que, L., Jr.; Ho, R. Y. N. *Chem. Rev.* **1996**, *96*, 2607. (b) Que, L., Jr. In *Iron Carriers and Iron Proteins*; Loehr, T. M., Ed.; VCH: New York, 1989; pp 467−524.

(2) (a) Ohlendorf, D. H.; Lipscomb, J. D.; Weber, P. C. *Nature* **1988**, *336*, 403. (b) Ohlendorf, D. H.; Orville, A. M.; Lipscomb, J. D. *J. Mol. Biol.* **1994**, *244*, 586. (c) Orville, A. M.; Elango, N.; Lipscomb, J. D.; Ohlendorf, D. H. *Biochemistry* **1997**, *36*, 10039. (d) Orville, A. M.; Lipscomb, J. D.; Ohlendorf, D. H. *Biochemistry* **1997**, *36*, 10052.

(3) (a) Han, S.; Eltis, L. D.; Timmis, K. N.; Muchmore, S. W.; Bolin, J. T. *Science* **1995**, *270*, 976. (b) Senda, T.; Sugiyama, K.; Narita, H.; Yamamoto, T.; Kimbara, K.; Fukuda, M.; Sato, M.; Yano, K.; Mitsui, Y. *J. Mol. Biol.* **1996**, *255*, 735.

(4) (a) Bertini, I.; Briganti, F.; Mangani, S.; Nolting, H. F.; Scozzafava, A. *Coord. Chem. Rev.* **1995**, *114*, 321. (b) Feig, A. L.; Lippard, S. J. *Chem. Rev.* **1994**, *94*, 759. (c) Shu, L.; Chiou, Y.-M.; Orville, A. M.; Miller, M. A.; Lipscomb, J. D.; Que, L., Jr. *Biochemistry* **1995**, *34*, 6649.

(5) (a) Que, L., Jr.; Kolanczyk, R. C.; White, L. S. *J. Am. Chem. Soc.* **1987**, *109*, 5373. (b) Cox, D. D.; Que, L., Jr. *J. Am. Chem. Soc.* **1988**, *110*, 8085. (c) Jang, H. G.; Cox, D. D.; Que, L., Jr. *J. Am. Chem. Soc.* **1991**, *113*, 9200.

(6) (a) Koch, W. O.; Krüger, H.-J. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2671. (b) Duda, M.; Pascaly, M.; Krebs, M. *J. Chem. Soc., Chem. Commun.* **1997**, 835.

(7) (a) Weller, M. G.; Weser, U. *J. Am. Chem. Soc.* **1982**, *104*, 3752. (b) Weller, M. G.; Weser, U. *Inorg. Chim. Acta* **1985**, *107*, 243. (c) Nishida, Y.; Shimo, H.; Kida, S. *J. Chem. Soc., Chem. Commun.* **1984**, 1611.

(8) (a) Dei, A.; Gatteschi, D.; Pardi, L. *Inorg. Chem.* **1993**, *32*, 1389. (b) Ito, M.; Que, L., Jr. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1342.

(9) Kitajima, N.; Tolman, W. B. *Prog. Inorg. Chem.* **1995**, *43*, 419 and references therein.

(10) (a) Ito, M.; Amagai, H.; Fukui, H.; Kitajima, N.; Moro-oka, Y. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 1937. (b) Hikichi, S.; Ogihara, T.; Fujisawa, K.; Kitajima, N.; Akita, M.; Moro-oka, Y. *Inorg. Chem.* **1997**, *36*, 4539.

(11) Synthetic procedures and characterization data (including X-ray work) for all new compounds are provided as Supporting Information.

(12) The structure of the DBCH-chelating Fe(II) complex has been reported: Chiou, Y.-M.; Que, L., Jr. *Inorg. Chem.* **1995**, *34*, 3577.

(13) Cox, D. D.; Benkovic, S. J.; Bloom, L. M.; Bradley, F. C.; Nelson, M. J.; Que, L., Jr.; Wallick, D. E. *J. Am. Chem. Soc.* **1988**, *110*, 2026.

(14) (a) Buchanan, R. M.; Kessel, S. L.; Downs, H. H.; Pierpont, C. G.; Hendrickson, D. N. *J. Am. Chem. Soc.* **1978**, *100*, 7894. (b) Boone, S. R.; Purser, G. H.; Chang, H.-R.; Lowery, M. D.; Hendrickson, D. N.; Pierpont, C. G. *J. Am. Chem. Soc.* **1989**, *111*, 2292. (c) Attia, A. S.; Conklin, B. J.; Lange, C. W.; Pierpont, C. G. *Inorg. Chem.* **1996**, *35*, 1033. (d) Lauffer, R. B.; Heistand, R. H., II.; Que, L., Jr. *Inorg. Chem.* **1983**, *22*, 50.

S0020-1669(97)01621-2 CCC: $15.00

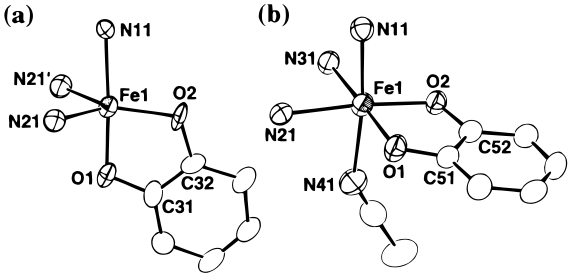

Figure 1. Structures of **2** (a) and **3**·MeCN (b) drawn at the 50% probability level. The Tp^{R} moieties except the metal-coordinating N atoms and the catecholate Bu^t groups are omitted for clarity.

around the Fe(III) center is similar to that of the inactive Fe(III)−substrate coordinated form of the extradiol enzyme.[3b] To our knowledge, **2** is the first example of the structurally characterized 5-coordinated trigonal-bipyramidal Fe(III) complex with the chelating catecholate ligand. However, further oxidative catechol ring cleavage was not observed probably due to the steric hindrance of the $\mathrm{Tp}^{\mathrm{Bu}^t,\mathrm{Pr}^i}$ ligand. Then, the less hindered 3,5-diisopropyl ligand was adopted in order to realize oxidative catechol cleavage.

The $\mathrm{Tp}^{\mathrm{Pr}^i_2}$ derivative, $\mathrm{Tp}^{\mathrm{Pr}^i_2}\mathrm{Fe}^{\mathrm{III}}$(DBC) (**3**), was prepared by reaction of the Fe(II) chloride complex, $\mathrm{Tp}^{\mathrm{Pr}^i_2}\mathrm{Fe}^{\mathrm{II}}\mathrm{Cl}$,[10a] with $\mathrm{DBCH_2}$ in the presence of $\mathrm{Et_3N}$ followed by chemical oxidation by $\mathrm{KMnO_4}$ in toluene.[16] However, the coordination environment of the metal center revealed by the X-ray crystallography of a purple single crystal of **3**·MeCN (obtained by recrystallization from a MeCN solution) was quite different from that of the above-mentioned $\mathrm{Tp}^{\mathrm{Bu}^t,\mathrm{Pr}^i}$ derivative **2**. The Fe(III) center has a 6-coordinate octahedral geometry containing one molecule of MeCN at the sixth coordination site. Two oxygen atoms of the chelating DBC ligand occupy the equatorial sites, and the Fe−O bond lengths of 1.929(3) and 1.969(3) Å are similar to those of the previously reported 6-coordinate Fe(III)−DBC complexes.[5] The catecholate C−O bond lengths of 1.334(5) and 1.340(5) Å are longer than those of semiquinonate C−O, although they are the shortest C−O lengths of the Fe(III)−DBC complexes.[5] It is notable that dissociation of the MeCN ligand was observed in solution. A purple MeCN solution exhibited two intense absorptions at 574 and 1046 nm which were similar to those found for $[\mathrm{Fe}^{\mathrm{III}}(\mathrm{6TLA})(\mathrm{DBC})]^+$,[12] but upon dissociation into toluene the color changed to deep blue ($\lambda_{\max} = 612$ nm in the 400−1200 nm range). Because the spectral feature of the toluene solution is clearly different from that of **2** which contains the trigonal-bipyramidal Fe(III) center (vide supra), the Fe(III) center of **3** must have a 5-coordinate square-pyramidal geometry in noncoordinating solvents.

As we expected, reaction of the Fe(III)−catecholato complex bearing the $\mathrm{Tp}^{\mathrm{Pr}^i_2}$ ligand **3** with $\mathrm{O_2}$ resulted in oxidative cleavage of DBC, and the reaction pattern was unique. The blue toluene solution of **3** changed to brown within 1 h upon exposure to $\mathrm{O_2}$ at room temperature. GC−MS analysis of organic products in the brown reaction mixture revealed that mainly extradiol cleavage occurred. Interestingly, intradiol cleavage was also observed as a minor side reaction, but no quinone product was detected.[17,18] In contrast, the trigonal-bipyramidal Fe(III)−DBC complex **2** was relatively stable under an $\mathrm{O_2}$ atmosphere; no spectral change (UV−vis−near-IR spectrum) was observed after exposure to $\mathrm{O_2}$ for 2 h.[19] On the basis of the reactivity of the $[\mathrm{Fe}^{\mathrm{III}}(\mathrm{DBC})(\mathrm{TACN})]^+$ complex, an $\mathrm{O_2}$ activation process by a 5-coordinate Fe(II)−semiquinonato species,[20] which is an alternative resonance structure of the Fe(III)−catecholato species, might be involved in the extradiol catechol cleavage.[8] In addition, recent spectroscopic and crystallographic studies of the extradiol enzymes have suggested that the substrate adduct has a 5-coordinate Fe(II) center with a vacant $\mathrm{O_2}$-binding position.[1,4c] Our observations are consistent with these hypotheses; the red shift of the LMCT band and the short C−O bond lengths of **3**·MeCN imply the semiquinonate character of the DBC ligand, and the square-pyramidal Fe center of **3** (in noncoordinating solvents) readily binds $\mathrm{O_2}$ to form an octahedral structure and activates $\mathrm{O_2}$ to carry out the extradiol ring cleavage (Scheme 1b). On the other hand, the trigonal-bipyramidal Fe(III) complex **2**, which is formed by $\mathrm{O_2}$ oxidation of the tetrahedral Fe(II) complex **1**, is relatively stable under the same conditions (Scheme 1a). The differences in reactivity toward oxidation between **3** and **2** may be attributed to the structural environments around the Fe centers (geometries of Fe, size of the Fe-surrounding cavities) tuned by Tp^{R}.[21]

In conclusion, by using the hindered $\mathrm{Tp}^{\mathrm{Bu}^t,\mathrm{Pr}^i}$ and $\mathrm{Tp}^{\mathrm{Pr}^i_2}$ ligands, structural and functional models for the catechol dioxygenases have been successfully prepared and characterized. Both of the Fe(III)−catecholato complexes, **2** and **3**, contain coordinatively unsaturated Fe(III) centers, but their geometries and reactivity toward $\mathrm{O_2}$ are considerably different. In particular, the $\mathrm{Tp}^{\mathrm{Pr}^i_2}$ complex **3** reacts with $\mathrm{O_2}$ to cause extradiol cleavage.[22,23] In order to elucidate factors determining the ring cleavage pattern, further investigations involving the detailed characterization and oxidation reaction analysis of a series of the Tp^{R}Fe−catecholato complexes are in progress.

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Supporting Information Available: ORTEP diagrams of **1**, **2**, **3**·MeCN, and **4**, summary of X-ray analysis, positional parameters, thermal parameters, and bond lengths and angles for **1**−**4**, and UV−vis−near-IR spectra of **2** and **3** (45 pages). Ordering information is given on any current masthead page.

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(15) The structures of Co(II)−, Cu(II)−, and Zn(II)−DBSQ (DBSQ = 3,5-di-*tert*-butyl-1,2-semiquinonate) complexes with the Tp^{R} ligand have been reported: Ruf, M.; Noll, B. C.; Groner, M. D.; Yee, G. T.; Pierpont, C. G. *Inorg. Chem.* **1997**, *36*, 4860.

(16) An Fe(II) μ-catecholato complex with the $\mathrm{Tp}^{\mathrm{Pr}^i_2}$ ligand, $\mathrm{Tp}^{\mathrm{Pr}^i_2}\mathrm{Fe}^{\mathrm{II}}(\mu\text{-DBC})\mathrm{Fe}^{\mathrm{II}}\mathrm{Tp}^{\mathrm{Pr}^i_2}$ (**4**, see Supporting Information), also reacted with $\mathrm{O_2}$ to give the Fe(III) catecholato complex **3**.

(17) The two isomers of the extradiol products were identified by comparison with the authentic compounds prepared according to ref 22c.

(18) In the TACN system, formation of the quinone product is major reaction and only a trace amount of the intradiol product is obtained in the absence of an additional aromatic N donor ligand (refs 8).

(19) Preliminary electrochemical analysis revealed oxidation potentials of $\mathrm{Tp}^{\mathrm{R}}\mathrm{Fe}^{\mathrm{III}}$(DBC) ($E^{\circ\prime}$(DBSQ/DBC), mV vs SCE, in $\mathrm{CH_2Cl_2}$, rt) as follows: for **2**, +206 mV; for **3**, +100 mV.

(20) Funabiki, T.; Tada, S.; Yoshioka, T.; Takano, M.; Yoshida, S. *J. Chem. Soc., Chem. Commun.* **1986**, 1699.

(21) Barbaro, P.; Bianchini, C.; Mealli, C.; Meli, A. *J. Am. Chem. Soc.* **1991**, *113*, 3181.

(22) Although the structures of the intermediates have not been revealed, some examples of catalytic extradiol catechol cleavage by iron, ruthenium, and vanadium compounds have been reported: Fe; (a) Funabiki, T.; Mizoguchi, A.; Sugimoto, T.; Tada, S.; Tsuji, M.; Sakamoto, H. Yoshida, S. *J. Am. Chem. Soc.* **1986**, *108*, 2921. (b) Funabiki, T.; Yoneda, I.; Ishikawa, M.; Ujiie, M.; Nagai, Y.; Yoshida, S. *J. Chem. Soc., Chem. Commun.* **1994**, 1453. Ru: (c) Matumoto, M.; Kuroda, K. *J. Am. Chem. Soc.* **1982**, *104*, 1433. V.: (d) Tatsuno, Y.; Tatsuda, M.; Otsuka, S. *J. Chem. Soc., Chem. Commun.* **1982**, 1100.

(23) Catechol 1,2-dioxygenase, which is the Fe(III) dependent intradiol enzyme, also carries out extradiol cleavage toward some substrate analogues: (a) Fujiwara, M.; Golovleva, L. A.; Saeki, Y.; Nozaki, M.; Hayaishi, O. *J. Biol. Chem.* **1975**, *250*, 4848. (b) Hou, C. T.; Patel, R.; Lillard, M. O. *Appl. Environ. Microbiol.* **1977**, *33*, 725. (c) Pascal, R. A., Jr.; Huang, D.-S. *Arch. Biochem. Biophys.* **1986**, *248*, 130.