Tilt/Asymmetry in Nitrosyl Metalloporphyrin Complexes: The Cobalt Case

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The nature of nitric oxide (NO) ligation in hemes has received renewed interest because of the recognition of NO participation in a wide variety of biological functions.[1] We recently found, in two crystalline polymorphs of the five-coordinate iron nitrosyl derivative [Fe(OEP)(NO)],[2,3] that the FeN_5 coordination group shows substantial deviation from expected axial symmetry. The deviations are a significant off-axis tilt of the Fe−N(NO) bond vector and an asymmetry in the equatorial $Fe-N_p$ bond distances. Reasons for the off-axis tilt are not immediately obvious. The equatorial asymmetry pattern is that the two $Fe-N_p$ bonds closest to the tilted Fe−N(NO) axial vector are effectively identical but significantly shorter than the other two $Fe-N_p$ bonds, which are also effectively equal. Since one of these structure determinations was carried out to extremely high resolution and a similar tilting/asymmetry pattern is also present in the structure of a related complex,[4] the equatorial asymmetry appears to be the result of subtle bonding effects correlated with the off-axis tilt. Moreover, there are hints of similar deviations from axial symmetry in previous structures of five-coordinate (porphinato)iron(II) nitrosyls. However, in these previous structure determinations,[5] disorder has limited the accuracy of the result. These observations strongly suggest that tilt/asymmetry in the coordination group is a hitherto unrecognized, fundamental property in (porphinato)-iron(II) nitrosyl systems.

While the need for a better understanding of the interaction of nitric oxide with metalloporphyrins is evident, there is also a similar need with other diatomic ligand interactions in heme proteins and iron porphyrins. A particular point of interest is the apparent asymmetric binding of CO in the heme proteins that is described as the “tilting” and/or “bending” of the CO group with respect to the heme plane. This binding mode has been regarded as the basis for the significant difference in CO affinity between iron porphyrins and the O_2-binding hemoproteins. Although there remains significant controversy about just how distorted the Fe−C−O linkage is,[6] a variety of mechanisms for explaining this distortion has been offered. The traditional explanation offered has been steric effects in the ligand binding pocket.[7] Recent work emphasized the importance of electrostatic interactions in the distal pocket,[8] or the proximal histidine residue,[9] or coupling of the FeCO tilting/bending mode[10] in controlling the distortion. Since the iron nitrosyl results[3] offered evidence that a structural distortion of a strongly bonding axial ligand can be a stable one and the distortion supported only by bonding effects, we have attempted to further characterize the effect. One approach has been to investigate different metalloporphyrin derivatives containing a bent nitrosyl group. Cobalt porphyrins are one such class and are especially interesting since they contain one additional electron in the critical $d_{z^2}-\pi^*(NO)$ molecular orbital. It is precisely this MO that must play an important role if the axial distortion is the result of bonding effects.[11] We report in this communication the structure determination of [Co(OEP)-(NO)], which has been carried out to high resolution.[13]

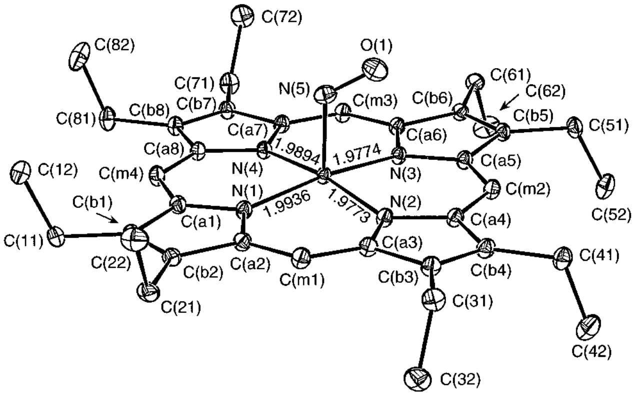

Figure 1. ORTEP diagram of [Co(OEP)NO] (50% probability ellipsoids). The labeling scheme is used in all diagrams and tables that are found in the Supporting Information. The direction of the 2.2° Co−N(NO) vector tilt from the normal to the porphyrin plane is between N(2) and N(3). Individual values of the four $Co-N_p$ bonds are shown. The standard uncertainty for each value is 0.0008 Å.

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(1) Stamler, J. S.; Singel, S. J.; Loscalzo, J. *Science* **1992**, *258*, 1898. Traylor, T. G.; Sharma, V. J. *Biochemistry* **1992**, *31*, 2847.

(2) Abbreviations: Porph, a generalized porphyrin dianion; OEP, the dianion of octaethylporphyrin; OETAP, the dianion of octaethyltetraazaporphyrin; N_p, porphyrinato nitrogen.

(3) Ellison, M. K.; Scheidt, W. R. *J. Am. Chem. Soc.* **1997**, *119*, 7404.

(4) Bohle, D. S.; Debrunner, P.; Fitzgerald, J.; Hansert, B.; Hung, C.-H.; Thompson, A. J. *J. Chem. Soc., Chem. Commun.* **1997**, 91.

(5) (a) Scheidt, W. R.; Frisse, M. E. *J. Am. Chem. Soc.* **1975**, *97*, 17. (b) Bohle, D. S.; Hung, C.-H. *J. Am. Chem. Soc.* **1995**, *117*, 9584. Nasri, H.; Haller, K. J.; Wang, Y.; Huynh, B. H.; Scheidt, W. R. *Inorg. Chem.* **1992**, *31*, 3459.

(6) The experimental results cited below have given a wide range of apparent Fe−C−O angles: (a) Kuriyan, J.; Wilz, S.; Karplus, M.; Petsko, G. A. *J. Mol. Biol.* **1986**, *192*, 133. (b) Teng, T.-Y.; Šrajer, V.; Moffat, K. *Nat. Struct. Biol.* **1994**, *1*, 701. (c) Cheng, X.; Schoenborn, B. P. *J. Mol. Biol.* **1991**, *220*, 381. (d) Moore, J. N.; Hansen, P. A.; Hochstrasser, R. M. *Proc. Natl. Acad. Sci. U.S.A.* **1988**, *85*, 5062. (e) Ormos, P.; Braunstein, D.; Frauenfelder, H.; Hong, M. K.; Lim, S.-L.; Sauke, T. B.; Young, R. D. *Proc. Natl. Acad. Sci. U.S.A.* **1988**, *85*, 8492. (f) Lim, M.; Jackson, T. A.; Anfinrud, P. A. *Science* **1995**, *269*, 962. (g) Ivanov, D.; Sage, J. T.; Keim, M.; Powell, J. R.; Asher, S. A.; Champion, P. A. *J. Am. Chem. Soc.* **1994**, *116*, 4139. (h) Quillan, M. L.; Arduini, R. M.; Olson, J. S.; Phillips, G. N., Jr. *J. Mol. Biol.* **1993**, *234*, 140. (i) Schlichting, I.; Berendzen, J.; Phillips, G. N., Jr.; Sweet, R. M. *Nature* **1994**, *371*, 808.

(7) Jameson, G. B.; Ibers, J. A. In *Bioinorganic Chemistry*; Bertini, I., Gray, H. B., Lippard, S., Valentine, J. S., Eds.; University Science Books: Mill Valley, CA, 1994; Chapter 4.

(8) (a) Balasubramanian, S.; Lambright, D. G.; Boxer S. G. *Proc. Natl. Acad. Sci. U.S.A.* **1993**, *90*, 4718. (b) Braunstein, D. P.; Chu, K.; Egeberg, K. D.; Frauenfelder, H.; Mourant, J. D.; Nienhaus, G. U.; Ormos, P.; Sligar, S. G.; Springer, B. A.; Young, R. D. *Biophys. J.* **1993**, *65*, 2447. (c) Li, T.; Quillin, M. L.; Phillips, G. N., Jr.; Olson, J. S. *Biochemistry* **1994**, *33*, 1433. (d) Springer, B. A.; Sligar, S. G.; Olson, J. S.; Phillips, G. N., Jr. *Chem. Rev.* **1994**, *94*, 699.

(9) Jewsbury, P.; Yamamoto, S.; Minato, T.; Saito, M.; Kitagawa, T. *J. Phys. Chem.* **1995**, *99*, 12677.

(10) Ghosh, A.; Bocian, D. F. *J. Phys. Chem.* **1996**, *100*, 6363.

(11) Hoffmann et al.[12] have predicted that bent nitrosyl ligands should display an off-axis movement of the nitrosyl nitrogen atom leading to a tilt. However, the direction predicted for the $\{MNO\}^8$ complexes considered is opposite to that observed in the iron system. To our knowledge, the study of Hoffmann et al.[12] is the only theoretical study to have addressed this point and no one has dealt with the equatorial asymmetry seen for the iron systems.

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Table 1. Bonding Parameters for [M(Porph)NO] Complexes

complex	M−N−O[a]	ΔM[b,c]	M−N(NO)[b]	N−O[b]	orientation[a,d]	tilt[a,e]	$M-N_p$[b,f]		ref
							short	long	
[Fe(OEP)NO] ($P\bar{1}$)	142.74(8)	0.27	1.7307(7)	1.1677(11)	40.2	8.2	1.999(1)	2.020(4)	3
[Fe(OEP)NO] ($P2_1/c$)	144.4(2)	0.29	1.722(2)	1.167(3)	37.9	6.5	1.991(3)	2.016(1)	3
[Fe(OETAP)NO] ($P\bar{1}$)	143.7(4)	0.31	1.721(4)	1.155(5)	39.6	7.6	1.924(2)	1.940(2)	4
[Co(OEP)NO] ($P\bar{1}$)	122.70(8)	0.16	1.8444(9)	1.1642(13)	45.0	2.2	1.977(1)	1.992(3)	this work

[a] Value in degrees. [b] Value in angstroms. [c] Metal atom displacement from 24-atom mean plane. [d] Dihedral angle of M−N−O and N_p −M−N(NO) planes. [e] Deviation from normal to porphyrin plane. [f] Estimated standard deviations calculated for two averaged values.

Crystalline [Co(OEP)(NO)][14] has a nitrosyl stretching frequency at 1677 cm^{-1} (KBr pellet); the solution values are 1676 cm^{-1} in $CHCl_3$ and 1670 cm^{-1} in CH_2Cl_2. The crystal structure determination[15] shows that the molecule is completely ordered, unlike the previously reported systems.[16,17] The derived results for the determination have the high precision and low standard uncertainties that are expected given the extensive, high-angle data measured. Figure 1 displays an ORTEP drawing of the [Co(OEP)(NO)] molecule. The Co−N_p bond distance average of 1.984(8) Å, the axial Co−N(NO) distance of 1.8444(9) Å, the Co−N−O angle of 122.70(8)°, and the 0.16 Å displacement of the cobalt atom from the mean plane are values that are consistent with those found for previous cobalt nitrosyls.[16,17] As shown in Figure S1 (Supporting Information), a formal diagram of the porphinato core in the [Co(OEP)(NO)] molecule, the core is almost exactly planar. Also shown in Figure S1 are the averaged bond distances and angles[18] for the chemically unique classes in the core. None of the averaged values warrant further comment. A comparison of the structure of [Co(OEP)(NO)] with the five-coordinate iron(II) analogues (Table 1) shows the major differences: the Co−N−O angle is ~21° smaller, the displacement of the cobalt atom from the porphinato plane is about half that of the iron atom, and the axial Co−N(NO) distance is about 0.12 Å larger. Figure S2 (Supporting Information) shows the arrangement of the pairs of [Co(OEP)(NO)] molecules that form weak dimers in the solid state.

Shown in Figure 1 is the orientation of the tilted nitric oxide ligand with respect to the porphyrin axis system; the tilt of the Co−N(NO) vector is between the pair of short Co−N_p bonds, i.e., N(2) and N(3). Importantly, the highly precise and ordered structure of [Co(OEP)(NO)] permits a detailed comparison with the unusual structural features of the two polymorphs of [Fe(OEP)(NO)][3] and that of [Fe(OETAP)(NO)].[4] These features are the interesting deviations from axial symmetry displayed by all three iron species. Table 1 gives values for a number of parameters in the four structures. Like the iron derivatives, [Co(OEP)(NO)] displays an off-axis tilt of the M−N(NO) bond vector and the same pattern of asymmetric distortions in the equatorial MN_4 plane. However, the tilt value of 2.2° is substantially smaller than the values observed in the iron species, where the tilt of the Fe−N(NO) vector is 6.5 or 8.2°.[19] Despite the smaller value of the axial tilt, the same asymmetric pattern of equatorial M−N_p bond distances remains. Since crystals of [Co(OEP)(NO)] and the second form of [Fe(OEP)(NO)] are isomorphous, the fact that different tilt angles are seen in the two structures buttresses our earlier conclusion that the tilt results from bonding effects rather than crystal packing. Indeed, the closest nonbonded O···H contact is opposite to that expected given the direction of the tilt.[20]

These cobalt results further suggest that there is a correlation between the value of the tilt and the equatorial distance asymmetry. Clearly the effect is subtle and will require careful theoretical calculations for complete understanding. That the addition of an electron in the axial $dz^2-\pi^*$(NO) molecular orbital plays an apparent, strong role in the tilt/asymmetry should provide an important constraint for theoretical studies. A final issue is the question of whether the tilt/asymmetry structural features now seen for four nitrosyl complexes are a general phenomenon in axially ligated metalloporphyrin species. If so, what types of axial ligand or ligands are required? Conclusive results will almost certainly require new structure determinations to provide the needed high-quality diffraction data. Searches for such systems are now underway.

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Supporting Information Available: Tables S1−S6, giving complete crystallographic details, atomic coordinates, complete bond distances and angles, anisotropic temperature factors, and fixed hydrogen atom positions, and Figures S1−S3, presenting additional structural diagrams (14 pages). The X-ray crystallographic file, in CIF format, is available. Ordering and Internet access information is given on any current masthead page.

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(12) Hoffmann, R.; Chen, M. L.; Elian, M.; Rossi, A. R.; Mingos, D. M. P. *Inorg. Chem.* **1974**, *13*, 2666.

(13) It is to be noted that nitrosylcobalt porphyrin derivatives have been used to probe hemoprotein structure and function. See, for example: (a) Yonetani, T.; Yamamoto, H.; Erman, J. E.; Leigh, J. S., Jr.; Reed, G. H. *J. Biol. Chem.* **1972**, *247*, 2447. (b) Hori, H.; Ikeda-Saito, M.; Leigh, J. S., Jr.; Yonetani, T. *Biochemistry* **1982**, *21*, 1431. (c) Yu, N.-Y.; Thompson, H. M.; Mizyukami, H.; Gersonde, K. *Eur. J. Biochem.* **1986**, *159*, 129. (d) Dierks, E. A.; Hu, S.; Vogel, K. M.; Yu, A. E.; Spiro, T. G.; Burstyn, J. N. *J. Am. Chem. Soc.* **1997**, *119*, 7316.

(14) [Co(OEP)NO] was prepared from 10 mg of Co(OEP) dissolved in dry chloroform solution (~5 mL) and several drops of pyridine in a narrow Schlenk tube. Purified NO was then bubbled through the solution. Single crystals were obtained by liquid diffusion using methanol (distilled over Mg) as the nonsolvent. Earlier preparations of [Co(OEP)NO] have been reported: Fujita, E.; Chang, C. K.; Fajer, J. *J. Am. Chem. Soc.* **1985**, *107*, 7665. Groombridge, C. J.; Larkworthy, L. F.; Mason, J. *Inorg. Chem.* **1993**, *32*, 379.

(15) A dark purple, rectangular block crystal of [Co(OEP)NO] (0.40 × 0.30 × 0.10 mm^3) was used for the structure determination. Data collection was carried out on an Enraf-Nonius FAST area-detector diffractometer with a Mo rotating-anode source ($\bar{\lambda}$ = 0.710 73 Å) using our methods for small-molecule X-ray data collection (Scheidt, W. R.; Turowska-Tyrk, I. *Inorg. Chem.* **1994**, *33*, 1314). Data collections were performed at 130(2) K. Complete crystallographic details are given in the Supporting Information (Table S1). The structure was solved using SHELXS-86 (Sheldrick, G. M. *Acta Crystallogr.* **1990**, *A46*, 467). The structure was refined against F^2 with the program SHELXL-93 (Sheldrick, G. M. *J. Appl. Crystallogr.*, in press). Hydrogen atoms were idealized with the standard SHELXL-93 idealization methods. A modified (Karaulov, A. I. School of Chemistry and Applied Chemistry, University of Wales, College of Cardiff, Cardiff CF1 3TB, U.K. Personal communication) version of the absorption correction program DIFABS (Walker, N. P.; Stuart, D. *Acta Crystallogr., Sect. A* **1983**, *A39*, 158) was applied.

(16) Scheidt, W. R.; Hoard, J. L. *J. Am. Chem. Soc.* **1973**, *95*, 8289.

(17) Richter-Addo, G. B.; Hodge, S. J.; Yi, G.-B.; Khan, M. A.; Ma, T.; Caemelbecke, E. V.; Guo, N.; Kadish, K. M. *Inorg. Chem.* **1996**, *35*, 6530−6538; **1997**, *36*, 2696.

(18) The number in parentheses following each averaged value is the estimated standard deviation calculated on the assumption that all averaged values are drawn from the same population.

(19) The main component of uncertainty in the tilt angles is the uncertainty in defining the mean plane of the porphyrin core. We estimate this at ~0.5°.

(20) A detailed examination of crystal packing distances shows no significantly short distances involving the nitrosyl ligand. An illustration showing the immediate environment of the NO is given in the Supporting Information.