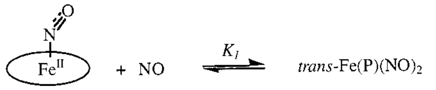
# Nitric Oxide Addition to the Ferrous Nitrosyl Porphyrins Fe(P)(NO) Gives *trans*-Fe(P)$(NO)_2$ in Low-Temperature Solutions

Ivan Lorković and Peter C. Ford*

*Department of Chemistry and Biochemistry*
*University of California, Santa Barbara*
*Santa Barbara, California 93106*

*Received January 28, 2000*
*Revised Manuscript Received April 24, 2000*

Ferrous porphyrins of the type $Fe^{II}$(TPP) (TPP = *meso*-tetraphenylporphinato dianion) undergo NO addition to give the paramagnetic mononitrosyl complex Fe(TPP)(NO) (**1**).[1,2] This has analogy in the reactions of NO with various ferrous heme proteins[3] including soluble guanylyl cyclase, NO's target in its role as a natural bioregulator in the cardiovascular system.[4] There are, however, significant ambiguities regarding the subsequent reactions of Fe(TPP)(NO) with excess NO. For example, this complex was reported to promote NO disproportionation[5] to give $N_2O$ and the nitrosyl nitro complex Fe(TPP)(NO)$(NO_2)$ in a manner similar to ruthenium porphyrins that were mechanistically probed in this laboratory.[6] Recently, however, we have demonstrated that ambient temperature solutions of Fe(TPP)(NO) display no changes in IR or optical spectra when treated with NO carefully cleaned of higher $NO_x$ impurities.[7] The latter observation is consistent with an earlier report by Wayland and Olson,[8] who, nonetheless, did conclude that Fe(TPP)(NO) reacts with NO reversibly to give the dinitrosyl Fe(TPP)$(NO)_2$ (**2**) in low-temperature solution, the supporting evidence being reversible disappearance of the ESR signal for Fe(TPP)(NO) under 400 Torr NO as $T$ was lowered. Another early report[9] suggests **2** to be formed by reaction of NO with **1** in ambient temperature toluene, although the optical spectral data appear consistent with formation of Fe(TPP)(NO)$(NO_2)$. To address these inconsistencies, we report here optical, infrared and NMR spectral data for NO reactions with Fe(TPP)(NO) and with Fe(TmTP)(NO), a more soluble analogue (TmTP = *meso*-tetra-*m*-tolyl-porphinato dianion). Spectra acquired in toluene-$d_8$, chloroform, and methylcyclohexane confirm the formation of a dinitrosyl complex Fe(P)$(NO)_2$ ($P$ = TPP, P = TmTP) in low-temperature solutions. Furthermore, these data argue for characterization of Fe(P)$(NO)_2$ as a centrosymmetric complex with equivalent trans nitrosyls (eq 1).



(1)

Figure 1 shows $^1$H NMR spectra of low-temperature (179 K) solutions prepared from Fe(TmTP)(NO) (~10 mM) in toluene-$d_8$ alone and in the presence of NO (10 mM). The toluene-$d_7$ impurity proton peaks appear at 7.15, 7.07, 6.98 (internal reference), and 2.07 ppm. In the absence of NO, the NMR spectrum shows considerable paramagnetic broadening, as expected for a $\{FeNO\}^7$ species. The only distinguishable peaks are broadened methyl (2.1 ppm), *meta* (8.2 ppm) and *para* (6.7 ppm) protons of the tolyl moiety; the *ortho* tolyl protons and $\beta$-pyrrole protons are too broad to locate. In the presence of NO (10 mM), however, all proton resonances sharpen and shift to nearly diamagnetic values, the $\beta$-pyrrole, and the *ortho*, *meta*, *para*, and methyl tolyl protons being observed at 8.94 (8H), 7.94 (8H), 7.39 (4H), 7.19 (4H), and 2.25 ppm (12H), respectively. This observation is indicative of the formation of a diamagnetic species we characterize as Fe(TmTP)$(NO)_2$. In contrast, no differences were observed between the 295 K spectra of Fe(TmTP)(NO) without and with added NO (10 mM); thus, there was no appreciable formation of a dinitrosyl complex at that temperature.

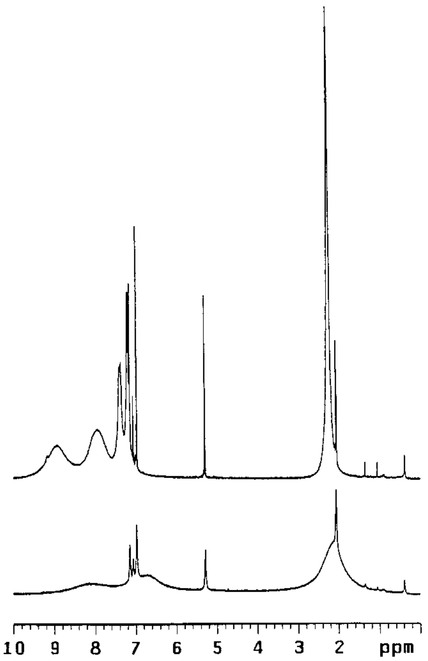


**Figure 1.** Bottom: $^1$H NMR spectrum of Fe(TmTP)(NO) (~10 mM) in toluene-$d_8$ at 179 K. Top: $^1$H NMR spectrum of this same solution with added NO (10 mM) at 179 K. The peak at 5.32 ppm represents a small amount of $CH_2Cl_2$ impurity. Both spectra represent the same number of scans obtained with identical parameters and are presented with the same vertical scale. The toluene-$d_7$ and $CH_2Cl_2$ resonances are slightly broadened in the presence of Fe(TmTP)(NO) alone.

For spectra recorded between 294 and 179 K, exchange between Fe(TmTP)(NO) (**3**) and Fe(TmTP)$(NO)_2$ (**4**) appears fast on the NMR time scale, since a single set of porphyrin protons were observed in the presence of NO at each $T$. These spectra also contain quantitative information regarding the equilibrium constant $K_1$. At a given $T$, the degree of peak sharpening arising from the presence of NO can be used to deduce $K_1$ using the expression: $K_1 = [\mathbf{4}]\,[\mathbf{3}]^{-1}[NO]^{-1} = \{(w - w_D)/(w_{NO} - w_D) - 1\}[NO]^{-1}$, where $w$ = the peak width (at half-height) of Fe(TmTP)(NO) in the absence of NO, $w_{NO}$ is the width in the

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* Corresponding author. E-mail: ford@chem.ucsb.edu.

[1] (a) Wayland, B. B.; Olson, L. W. *J. Chem. Soc., Chem. Commun.* **1973**, 897−898. (b) Scheidt, W. R.; Frisse, M. E. *J. Am. Chem. Soc.* **1975**, *97*, 17−21.

[2] $\{MNO\}^7$ in the Enemark−Feltham formalism. Enemark, J. H.; Feltham, R. D. *J. Am. Chem. Soc.* **1974**, *96*, 5002−5004.

[3] (a) Traylor, T. G.; Sharma, V. S. *Biochemistry* **1992**, *31*, 2847−2849. (b) Radi, R. *Chem. Res. Toxicol.* **1996**, *5*, 828−835. (c) Feelisch, M.; Stamler, J. S. (Eds.) *Methods in Nitric Oxide Research*; Wiley: Chichester, UK, 1996, and refs therein.

[4] (a) Kim, S.; Deinum, G.; Gardner, M. T.; Marletta, M. A.; Babcock, G. T. *J. Am. Chem. Soc.* **1996**, *118*, 8769−8770. (b) Burstyn, J. N.; Yu, A. E.; Dierks, E. A.; Hawkins, B. K.; Dawson, J. H. *Biochemistry* **1995**, *34*, 5896−5903.

[5] (a) Yoshimura, T. *Inorg. Chim. Acta* **1984**, *83*, 17−21. (b) Settin, M. F.; Fanning, J. C. *Inorg. Chem.* **1988**, *27*, 1431−1435. (c) Ellison, M. K.; Schulz, C. E.; Scheidt, W. R. *Inorg. Chem.* **1999**, *38*, 100−108.

[6] (a) Lorković, I. M.; Ford, P. C. *Inorg. Chem.* **1999**, *38*, 1467−1473. (b) Miranda, K. M.; Bu, X.; Lorković, I. M.; Ford, P. C. *Inorg. Chem.* **1997**, *36*, 4838−4848. (c) Lorković, I. M.; Ford, P. C. *J. Chem. Soc., Chem. Commun.* **1999**, 1225−1226.

[7] Lorković, I. M.; Ford, P. C. *Inorg. Chem.* **2000**, *39*, 632−633.

[8] Wayland, B. B.; Olson, L. W. *J. Am. Chem. Soc.* **1974**, *96*, 6037−6041.

[9] Lançon, D.; Kadish, K. M. *J. Am. Chem. Soc.* **1983**, *105*, 5610−5617.

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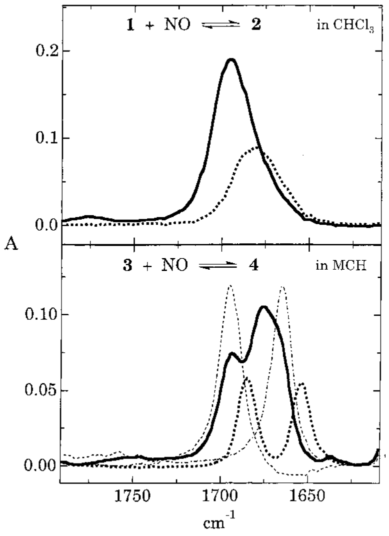

**Figure 2.** Top: Infrared spectra of solution prepared from Fe(TPP)-(NO) (2.3 mM) and NO (8 mM) in $CHCl_3$ at 295 K (dashed line) and at 213 K (solid line). Bottom: FTIR spectra of a methylcyclohexane solution of Fe(TmTP)(NO) (1 mM) in the presence of 1:1 $^{14}NO$:$^{15}NO$ (8 mM total) at 295 K (dashed line) and at ∼179 K (solid line), showing the transformation of isotopically mixed Fe(TmTP)(NO) (**3**) to isotopically mixed $Fe(TmTP)(NO)_2$ (**4**). The ∼179 K spectra of **4** prepared using pure $^{15}NO$ and pure $^{14}NO$ (thin dashed lines) at 1696 and 1665 $cm^{-1}$, respectively, are also shown. Bands in bottom spectra are sharper owing to the hydrocarbon solvent.

presence of NO, and $w_D$ is the width of a diamagnetic species such as the monoprotio solvent impurity. From the half-height widths of the tolyl methyl proton resonance for a 1 mM solution of Fe(TmTP)(NO) ([NO] = 10 mM), values of $K_1$ were estimated at $T$ between 253 K (23 $M^{-1}$) and 179 K (3100 $M^{-1}$) and the thermodynamic parameters for eq 1 found to be $\Delta H° = -6.7 \pm 0.8$ kcal/mol and $\Delta S° = -21 \pm 4$ cal $(K/mole)^{-1}$.[10] Similar results were seen upon cooling a $CDCl_3$ solution of Fe(TPP)(NO) to 210 K in the presence and absence of NO.

Figure 2 shows FTIR spectra recorded for solutions of Fe-(TPP)(NO) (2.3 mM) in $CHCl_3$ at room temperature and at 213 K. In the absence of added NO, cooling this solution had no effect on the nitrosyl stretching band ($\nu_{NO}$ = 1681 $cm^{-1}$, $\epsilon$ = 800 $M^{-1}$ $cm^{-1}$), except for a slight band intensification due to thermal solvent contraction. Furthermore, addition of NO (8 mM) to a room-temperature solution of Fe(TPP)(NO) had no effect on the shape or intensity of this band.[7] However, cooling the latter solution to 213 K resulted in the appearance of a new band at 1695 $cm^{-1}$ with twice the intensity (∼1600 $M^{-1}$ $cm^{-1}$), and another much weaker band at 1777 $cm^{-1}$. The positions and relative intensities of these are consistent with a *trans* arrangement of equivalent nitrosyl ligands, that is, $Fe(TPP)(NO)_2$.

An analogous experiment was carried out with the more soluble Fe(TmTP)(NO) and a 50:50 mixture of $^{14}NO$/$^{15}NO$ (8 mM total NO) in methylcyclohexane (Figure 2). The room-temperature spectrum shows two $\nu_{NO}$ bands at 1683 and 1654 $cm^{-1}$ consistent with a ∼50/50 mixture of Fe(TmTP)($^{14}NO$) and Fe(TmTP)($^{15}NO$), respectively. Cooling to ∼173 K gave an IR spectrum with overlapping bands at 1694, 1676, and 1665 $cm^{-1}$ in an intensity ratio (∼ 1:2:1) consistent with formation of unlabeled, mixed labeled, and fully labeled $Fe(TmTP)(NO)_2$ in a statistical distribution. Low-temperature IR spectra of $Fe(TmTP)(NO)_2$ prepared with pure $^{14}NO$ and with pure $^{15}NO$ are also shown.[11]

Supplemental Figure S-1 shows UV−vis spectra obtained from cooled (∼173 K) methylcyclohexane solutions of Fe(TmTP)(NO) (∼200 $\mu$M) in the absence of NO and of $Fe(TmTP)(NO)_2$ in the presence of NO (8 mM). The Q and Soret bands for Fe(TmTP)-$(NO)_2$ occur at 540 nm (1.5 × $10^4$ $M^{-1}$ $cm^{-1}$) and 416 nm (1.4 × $10^5$ $M^{-1}$ $cm^{-1}$), respectively, compared to 536 nm (9 × $10^3$ $M^{-1}$ $cm^{-1}$) and 404 nm (1.0 × $10^5$ $M^{-1}$ $cm^{-1}$) for Fe(TmTP)-(NO). The Soret band for $Fe(TmTP)(NO)_2$ is clearly distinguishable from that for $Fe(TmTP)(NO)(NO_2)$ (432 nm).[7] Analogous experiments using Fe(TPP)(NO) in $CHCl_3$ give analogous results (supplemental Figure S-2). It is important to note that the NMR, IR, and UV−vis spectral features of $Fe(TPP)(NO)_2$ and Fe-$(TmTP)(NO)_2$ revert to those of Fe(TPP)(NO) and Fe(TmTP)-(NO) upon warming to room temperature.

To summarize, we have observed reversible formation of Fe-$(P)(NO)_2$ from NO plus Fe(P)(NO) in low-temperature solutions by NMR, IR, and UV−vis spectroscopy. The NMR data indicate this species to be diamagnetic, while the IR data point to a centrosymmetric *trans*-dinitrosyl configuration. However such solutions *do not* undergo further reaction under these conditions. Although it is not clear why the behavior of the Fe(P)(NO) system is different from that of the analogous ruthenium porphyrins[6] and that recently reported for the non-heme iron complex,[12] the present data show that the ferro-heme center does not support NO disproportionation to $N_2O$ plus $Fe(P)(NO)(NO_2)$.

**Acknowledgment.** This work was supported by the National Science Foundation (CHE 9726889). We thank Dr. Steve Massick and Jon Marhenke for expertise in assembly of the low temperature IR/UV−vis cell.

**Supporting Information Available:** Included is Figure S-1 displaying the optical spectra of Fe(TmTP)(NO) and $Fe(TmTP)(NO)_2$ in 179 K methylcyclohexane, Figure S-2 (in black and white and in color) displaying the reversibility of optical spectral changes as a $CHCl_3$ solution of Fe(TPP)(NO) and NO (8 mM) is cooled then rewarmed (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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[10] (10) (a) The [NO] for the equilibrated toluene solution at 295 K was calculated to be 10 mM from published solubility data,[10b] and [NO] was assumed to be the same value at the lower $T$ as well. Assumption of minimal net transport between headspace and solution can be rationalized on two bases. First, the gas/liquid interface is small relative to the liquid volume in the closed NMR tube, and thus transport will be slow. Furthermore, although NO solubility in toluene (units: mol $L^{-1}$ $atm^{-1}$) increases with decreasing $T$, $P_{NO}$ correspondingly drops so that increases in $[NO]_{equilibrium}$ are minor (<10% from 295 to 213 K). Since no hysteresis was observed in peak width measurements as $T$ was decreased and increased, we conclude that net transport leading to changes in [NO] is minimal under these conditions. (b) Shaw, A. W.; Vosper, A. J. *J. Chem. Soc. Faraday Trans.* **1977**, *73*, 1239−1244. These authors measured NO solubility in toluene for 22 temperatures between 213 and 289 K. Values outside that temperature range were estimated by extrapolation.

[11] (11) (a) Peak separations corresponding to different degrees of $^{14}NO$/$^{15}NO$ labeling is greater between unlabeled and singly labeled (18 $cm^{-1}$) than between singly and fully labeled (11 $cm^{-1}$). An analogous pattern was observed for the correspondingly labeled $Ru(TmTP)(NO)_2$ which displayed bands at 1641, 1624, and 1613 $cm^{-1}$, respectively.[10b] (b) Lorković, I. M.; Ford, P. C. manuscript in preparation.

[12] (12) Franz, K. J.; Lippard, S. J. *J. Am. Chem. Soc.* **1999**, *121*, 10504−10512.