Spectroelectrochemical Characterization of Substituted Cobalt Nitrosyl Porphyrins

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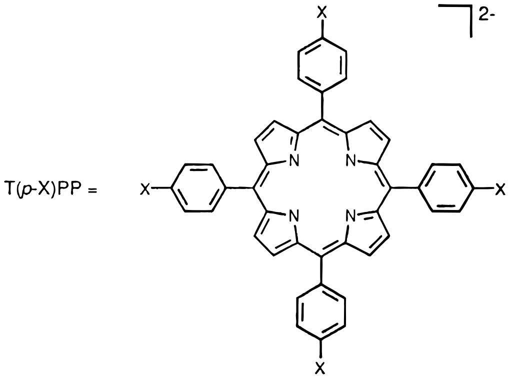
Introduction

Nitrosyl metalloporphyrins have been studied extensively over the past 2 decades and characterized by numerous spectroscopic, electrochemical, and structural techniques.[1−5] The importance of nitrosyl metalloporphyrins in human physiology gains greater importance in light of the fact that nitric oxide has been found to target heme-containing proteins.[6] The cobalt nitrosyl porphyrin CoTPP(NO) (TPP = tetraphenylporphyrin dianion) has been used as a model for metalloporphyrin−nitric oxide interaction.[7] The *para* positions of the *meso* phenyl rings on TPP are readily substituted, allowing the series of CoT(*p*-X)PP(NO) (X = H, **1**; OMe, **2**; NO_2, **3**) compounds to be synthesized.



CoT(*p*-X)PP(NO); X = H (**1**), OMe (**2**), NO_2 (**3**)

The unsubstituted species CoTPP(NO) (**1**) undergoes two reversible oxidations in CH_2Cl_2 (eqs 1 and 2). The single electron oxidation of **1** has also been studied by spectroelectrochemistry.[7] The first oxidation is believed to be localized within the conjugated π system of the porphyrin ring, whereas the second oxidation is postulated to be metal centered. The first oxidation product $[CoTPP(NO)]^+$ (1^+) has been observed using infrared spectroelectrochemistry, but the second oxidation product has not been detected spectroscopically.[7] This is attributed to the rapid dissociation of NO from $[CoTPP(NO)]^{2+}$ during controlled-potential electrolysis at the second oxidation potential. Herein, we describe infrared spectroelectrochemical studies on the series of cobalt nitrosyl porphyrins **1**−**3** and report the observation of NO binding in the doubly oxidized complexes, $\mathbf{1}^{2+}$−$\mathbf{3}^{2+}$. Functionalization of TPP at its *meso* phenyl *para* position was found to modulate the cobalt−nitric oxide interaction. The attachment of electron-donating or -withdrawing substituents on the porphyrin ring system alters the electronic properties of the porphyrin ring and influences the binding of nitric oxide to the metalloporphyrin.

$$\mathrm{CoTPP(NO)} \rightarrow [\mathrm{CoTPP(NO)}]^+ + e^- \qquad E_{1/2} = 1.01\ \mathrm{V}\ vs\ \mathrm{SCE} \tag{1}$$

$$[\mathrm{CoTPP(NO)}]^+ \rightarrow [\mathrm{CoTPP(NO)}]^{2+} + e^- \qquad E_{1/2} = 1.25\ \mathrm{V}\ vs\ \mathrm{SCE} \tag{2}$$

Experimental Section

General Procedures. All moisture sensitive reactions were carried out under nitrogen or argon in oven dried glassware using drybox or standard Schlenk techniques. The syntheses of $T(p\text{-}X)PPH_2$ (X = H, OMe, NO_2) were adapted from published procedures.[8−10] Metalloporphyrins were either purchased from Midcentury Chemicals or synthesized by adaptations of literature procedures.[11,12] Nitric oxide was purchased from Matheson and passed through a column of KOH pellets before use to remove higher oxides of nitrogen. Flash column chromatography was performed using silica gel 60G (EM Science, 230−400 mesh) or alumina (Fisher Scientific, 80−200 mesh). Ultraviolet−visible spectra were obtained using a Hitachi U-2000 spectrophotometer. Infrared spectra were obtained as films in dichloromethane (CH_2Cl_2) using a Mattson Research Series spectrometer.

Electrochemistry. Tetrabutylammonium hexafluorophosphate (TBAP) was purchased from Aldrich, recrystallized from ethanol, dried at 120 °C under vacuum for 24 h, and subsequently stored in a drybox. Cyclic voltammetry experiments were conducted in CH_2Cl_2 with 0.1 M TBAP as the supporting electrolyte. Dichloromethane was distilled under nitrogen from CaH_2 prior to use.

Infrared Spectroelectrochemistry (SEC). The design of the reflectance IR spectroelectrochemical cell used in the nitrosyl metalloporphyrin study was reported previously and is based on the cell originally used by Mann and co-workers.[13] Infrared spectral changes accompanying thin-layer bulk electrolyses were measured using a flow-through spectroelectrochemical cell. All spectroelectrochemical experiments were carried out using 5 mM CH_2Cl_2 solutions of CoT(*p*-X)PP(NO) with 0.1 M TBAP as the supporting electrolyte. All solutions were prepared in a drybox and were degassed completely before injection into the spectroelectrochemical cell. Blank CH_2Cl_2 solutions of 0.1 M TBAP were used for the FT-IR difference spectra. A PAR Model 175 universal programmer with a PAR Model 176 Current Follower was used to effect and monitor thin layer bulk electrolyses. The IR spectra were acquired using a Mattson Research Series FTIR with an external sampling port and a MCT (mercury−cadmium−telluride) detector.

Synthesis of CoT(*p*-X)PP(NO) (X = H, 1; OMe, 2; NO_2, 3). The nitrosylated cobalt porphyrins CoT(*p*-X)PP(NO) (X = H, **1**; OMe, **2**; NO_2, **3**) were synthesized by adapting a procedure described by Scheidt and Hoard.[5] The cobalt porphyrins (CoT(*p*-X)PP; 200 mg) were dissolved in dichloromethane and carefully degassed. Dry piperidine (1.5 mL) was added and NO was bubbled through a potassium hydroxide (KOH) scrubber and into the solution as a steady stream for

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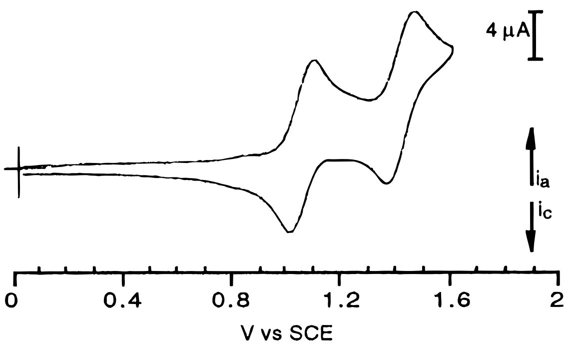

Figure 1. Cyclic voltammogram of CoT(*p*-OMe)PP(NO) (**2**) in CH_2Cl_2 with 0.1 M TBAP as supporting electrolyte, V *vs* SCE.

Table 1. Electrochemical Data for CoT(*p*-X)PP(NO)

	X	$E_{1/2}$(+/0)[a]	$E_{1/2}$(+/2+)[a]	Hammet[b] σ_p
1	H	1.00 (1.01)[c]	1.37 (1.25)[c]	0
2	OMe	0.99	1.31	−0.28
3	NO_2	1.38	1.49	0.81

[a] Cyclic voltammograms recorded in CH_2Cl_2, V *vs* SCE. [b] March, J. M. *Advanced Organic Chemistry: Reactions, Mechanisms, and Structures*; Wiley: New York, 1985; p 244. [c] Values in paretheses are those obtained by Kadish *et al.*: see Kadish, K. M.; Mu, X. H.; Lin, X. Q. *Inorg. Chem.* **1988**, *27,* 1489.

0.5 h. The solution was purged with nitrogen to remove excess NO and subsequently heated to boiling. The nitrosyl porphyrin precipitated after addition of degassed methanol. Products **1**−**3** were filtered and dried under aspirator vacuum. The yields of the nitrosylated metalloporphyrins **1**−**3** were *ca.* 50%.

Results and Discussion

The cyclic voltammograms of the −OMe and $-NO_2$-substituted porphyrins displayed two reversible single electron oxidations, similar to those reported for CoTPP(NO).[7] A representative cyclic voltammogram of CoT(*p*-OMe)PP(NO) is shown in Figure 1 and the oxidation potentials for **1**−**3** are collected in Table 1.

The most striking feature of the data found in Table 1 is the large anodic shift in the first oxidation potential $E_{1/2}(0/+)$ observed for the nitro-substituted porphyrin **3**, compared to **1** and **2**. The difference in $E_{1/2}(0/+)$ between **1** and **2** was small (ΔE = 10 mV), and indicated that the change from CoTPP(NO) to CoT(*p*-OMe)PP(NO) only slightly perturbed the electronic environment of the porphyrin ring. This is in sharp contrast to the large 380 mV anodic shift in $E_{1/2}(0/+)$ observed for CoT(*p*-NO_2)PP(NO). These observations are consonant with the differences in Hammet σ_p values for the *meso* phenyl substituents (Table 1).[14] The moderate electron-donating −OMe group caused only a slight cathodic variation in $E_{1/2}(0/+)$ while the strongly electron-withdrawing $-NO_2$ group effected a large anodic shift in $E_{1/2}(0/+)$. Comparatively smaller differences in the second oxidation potentials $E_{1/2}(+/2+)$ for **1**−**3** were observed. Thus, the data in Table 1 are consistent with the conclusion that the first oxidation of CoT(*p*-X)PP(NO) is porphyrin ring based.[7,10] Substitution of the porphyrin primarily affected the first oxidation potential while the second metal-centered oxidation potential was little changed.

The infrared spectra of **1**−**3** (Table 2) also showed substituent effects. The $-NO_2$ group caused a significant increase ($\Delta\nu$ = 12 cm^{-1}) in the $\nu(N{\equiv}O)$ band compared to CoTPP(NO) whereas the −OMe substituent resulted in only a small decrease ($\Delta\nu$ = 2 cm^{-1}) in $\nu(N{\equiv}O)$. The increase in $\nu(N{\equiv}O)$ for **3**, as compared to **1** and **2**, is attributed to a decrease in porphyrin to cobalt electron donation. The decreased electron density at the Co center reduces π back-bonding, and thereby increases the N≡O stretching frequency. A similar explanation can be applied to the decrease in the N≡O stretching frequency for **2**. In this case, the electron-donating −OMe group decreased $\nu(N{\equiv}O)$ by increasing the electron donating properties of the porphyrin ring. Again, the magnitude and direction of the changes in $\nu(N{\equiv}O)$ observed with *meso* phenyl substitution are in accord with Hammet σ_p values.[14]

Table 2. Spectroelectrochemical Data for CoT(*p*-X)PP(NO)

		FT-IR ($\nu_{N\equiv O}$, cm^{-1})[a]		
	X	CoT(*p*-X)-PP(NO)	[CoT(*p*-X)-PP(NO)]$^+$	CoT(*p*-X)-PP(NO)]$^{2+}$
1	H	1682	1726	1756
2	OMe	1680	1722	1746
3	NO_2	1694	1732	1779

[a] Recorded in CH_2Cl_2 in spectrolectrochemical cell.

Solution spectroelectrochemical studies were carried out on **1**−**3**. The spectral changes observed at the two oxidation potentials are shown in Figures 2 and 3, and the $\nu(N{\equiv}O)$ data for each oxidation state are collected in Table 2. The application of potentials just anodic of the first oxidation potential to CH_2Cl_2 solutions of **1**−**3** resulted in the smooth conversion of CoT(*p*-X)PP(NO) to [CoT(*p*-X)PP(NO)]$^+$, as monitored by infrared spectroelectrochemistry (Figure 2).

The observed spectral changes were fully reversible and, in each case, single electron oxidation caused a *ca.* 40 cm^{-1} increase in $\nu(N{\equiv}O)$. As expected, the $\nu(N{\equiv}O)$ absorption band for **3** was observed at the highest frequency (1732 cm^{-1}) in the singly-oxidized state, while $\nu(N{\equiv}O)$ for **2** was detected at the lowest frequency (1722 cm^{-1}). The second oxidations of **1**−**3** were also studied and reasonably smooth conversions were observed (Figure 3). A notable result of our studies is that $\nu(N{\equiv}O)$ absorption bands were observed for all doubly oxidized [CoT(*p*-X)PP(NO)]$^{2+}$ (X = H, OMe, NO_2) species. The $\nu(N{\equiv}O)$ band for the doubly oxidized [CoTPP(NO)]$^{2+}$ had eluded observation in an earlier study.[7] The observed $\nu(N{\equiv}O)$ absorption bands of the doubly-oxidized species followed the Hammet σ_p values with **2** having the lowest $\nu(N{\equiv}O)$ frequency (1746 cm^{-1}) and **3** the highest (1779 cm^{-1}). Upon oxidation of **2** to [CoT(*p*-OMe)PP(NO)]$^{2+}$ a broad $\nu(N{\equiv}O)$ band was observed while the two electron oxidations of **1** and **3** gave rise to sharp, well-defined $\nu(N{\equiv}O)$ bands. The second oxidations for all the three porphyrins were reversible, although intensity losses in the $\nu(N{\equiv}O)$ absorption bands occurred when solutions of **1**−**3** were maintained at the second oxidation potentials for extended periods of time. This loss in intensity was attributed to the instability and ensuing decomposition of [CoT(*p*-X)PP(NO)]$^{2+}$.[7] The observed instability of [CoT(*p*-X)PP(NO)]$^{2+}$ is expected in light of previous reports regarding the oxidation of CoTPP(NO). Kadish has proposed a possible decomposition pathway for [CoTPP(NO)]$^{2+}$ in which NO liberation is subsequently followed by further oxidation of [CoTPP]$^{2+}$ at the working electrode.[7] The NO dissociation pathway is plausible based on measured $E_{1/2}(2+/3+)$ oxidation potentials for [CoT(*p*-X)PP]$^{2+}$ (X = H, +1.23 V; OMe, +1.21 V; NO_2, +1.40 V *vs* SCE). The potentials required to electrochemically generate [CoT(*p*-X)PP(NO)]$^{2+}$ are sufficiently anodic to immediately oxidize [CoT(*p*-X)PP]$^{2+}$, produced by NO dissociation, to [CoT(*p*-X)PP]$^{3+}$. The Co→NO π back-

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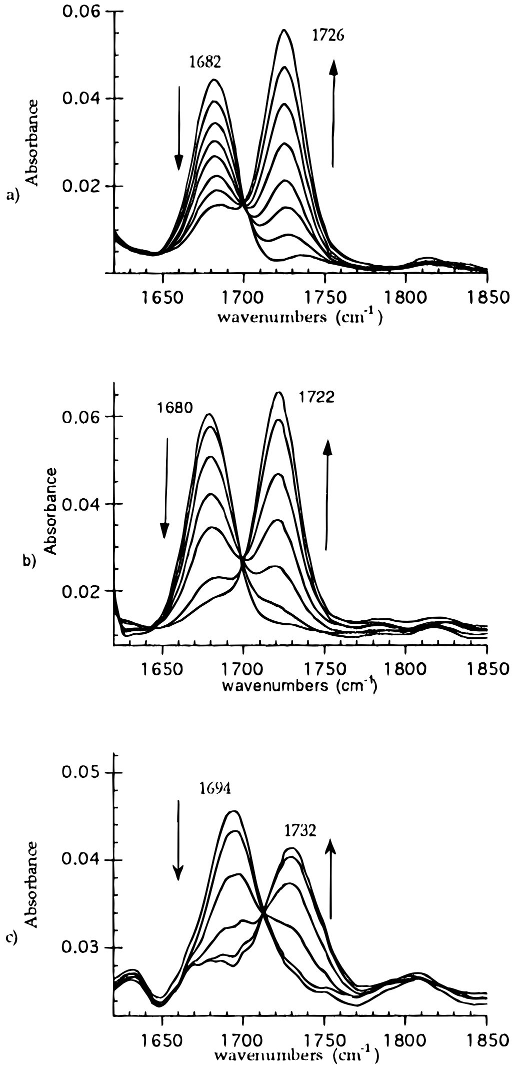

Figure 2. IR spectral changes in the $\nu(N\equiv O)$ region following oxidation of CoT(*p*-X)PP(NO) to [CoT(*p*-X)PP(NO)]$^{+}$: (a) X = H, **1**; (b) X = OMe, **2**; (c) X = NO_2, **3**.

bonding contribution in [CoT(*p*-X)PP(NO)]$^{2+}$ is expected to be small due to the presence of a Co(III) center. This suggests that the Co−NO bonding interaction in CoT(*p*-X)PP(NO)]$^{2+}$ should be principally σ in character with the nitric oxide acting primarily as a weak donor ligand. This is consistent with the proposed lability of NO and the negligible variation in the observed stabilities of [CoT(*p*-X)PP(NO)]$^{2+}$ with *meso* phenyl substituent. The instability of the doubly-oxidized forms of **1**−**3** enjoins the use of infrared spectroelectrochemsitry for the *in situ* generation and subsequent spectroscopic studies of the chemical reactivity of [CoT(*p*-X)PP(NO)]$^{2+}$.

Summary

Nitrosyl metalloporphyrin interactions were modulated by changing the functional group at the *para* position of the *meso* phenyl ring in a series of compounds CoT(*p*-X)PP(NO) (X = H, OMe, NO_2). Cyclic voltammetry indicated that porphyrin ring substitution primarily affected the first oxidation potential, which is expected to be porphyrin ring based. Comparatively smaller effects were observed for the second, metal-based, oxidation potential. We also demonstrated that the strength of the cobalt nitrosyl interaction, as monitored by $\nu(N\equiv O)$, can be controlled by varying the substituents on the porphyrin ring.

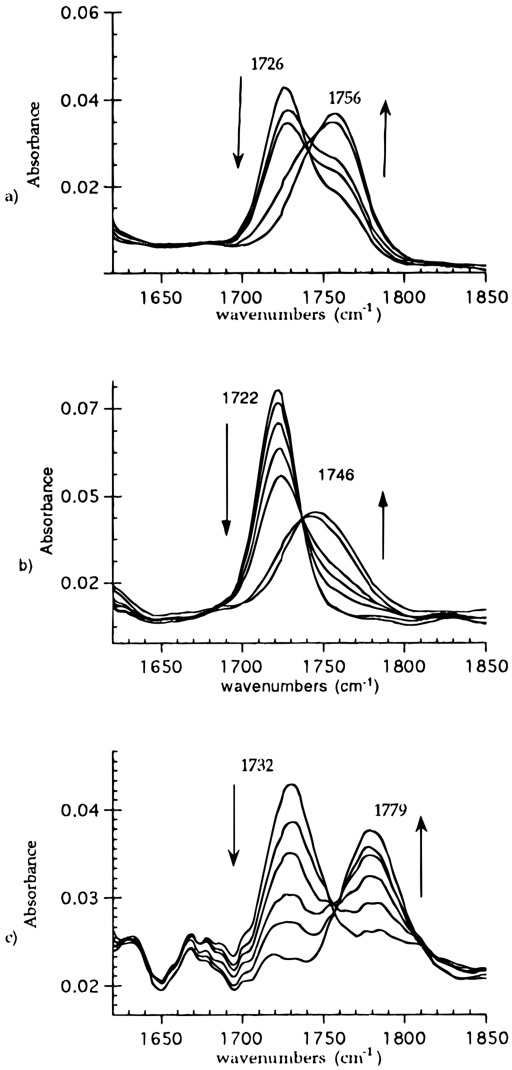

Figure 3. IR spectral changes in the $\nu(N\equiv O)$ region following oxidation of [CoT(*p*-X)PP(NO)]$^{+}$ to [CoT(*p*-X)PP(NO)]$^{2+}$: (a) X = H, **1**; (b) X = OMe, **2**; (c) X = NO_2, **3**.

Precedence for this observation is reported for iron nitrosyl porphyrins whereby functionalization was shown to alter the infrared $\nu(N\equiv O)$ stretch.[15] Reflectance infrared spectroelectrochemical experiments were undertaken to further investigate the electrochemical properties. For all three compounds studied, $\nu(N\equiv O)$ bands were observed for the first *and* second oxidation products, a feature previously unreported. The spectroelectrochemical studies also implied that the Co−NO bonding in the CoT(*p*-X)PP(NO)]$^{2+}$ species of **1**−**3** was mainly σ in character.

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