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Preparation of Polyetherol-Appended Sulfur Porphyrazines and Investigations of Peripheral Metal Ion Binding in Polar Solvents

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We describe the complete synthesis and characterization of a new family of peripherally functionalized porphyrazines (pz's) with four, three, or two (in a trans conformation) bis[thioethoxy(ethoxy)ethanol] moieties appended at the pyrroles. These "polyetherol" groups serve as weak exocyclic binding sites for a number of metal ions and also provide solubility of the pz's in low molecular-weight alcohols and water. Electronic spectra of the modified porphyrazines exhibit distinct changes in the visible region (both absorbance and fluorescence) in response to treatment with Ag^+, Pb^{2+}, Cd^{2+}, Cs^+, and Ni^{2+} in solution. Such properties make these compounds intriguing candidates for incorporation into the transducer layers in optically based chemical sensors.

Introduction

As part of a development of functionalized porphyrazines (pz) with multiple metal-ion binding sites,[1−3] we previously reported on the preparation of a tetra-S_2O_3 crown-porphyrazine and demonstrated changes in the optical spectra brought about by peripheral metal-ion binding.[4] More recently, we have reported a method to preferentially prepare unsymmetrical porphyrazines of the form $M[pz(A_n:B_{4-n})]$ with $n = 4$, 3, and 2 (in a trans conformation) where A is widely variable and B is a fused α,α'-diisopropyloxybenzo ring.[5] The porphyrazines corresponding to each value of n show unique absorption and emission characteristics that reflect the symmetry of the molecule, in agreement with theoretical models.[6,7] Furthermore, the alkoxy substituents at the α-positions of the fused benzo rings in the $n = 3$ and 2 pz's cause a Q-band absorbance shift toward longer wavelengths.[8]

Here, we report the synthesis of a new family of unsymmetrical porphyrazines (Figure 1) with thioethoxy(ethoxy)ethanol groups appended to the periphery of the macrocycle. These "polyetherol" side chains not only serve to chelate metal ions but also greatly enhance the solubilities of these molecules in protic solvents such as low molecular-weight alcohols and even water. By variation of the molecular symmetry, it is possible to generate molecules that maintain many of the chemical binding properties inherent in this class of macrocycles while fine-tuning the absorbance and emission profiles.

This combination of properties, along with the high molar absorptivities inherent in pz molecules, makes them intriguing candidates for metal-ion detection. Achieving true selectivity of analyte interaction with chemical sensors continues to be an elusive goal for many applications. The presence of interferants at high analyte concentrations often does not allow an accurate, direct quantification of the species of interest without sample pretreatment, which can significantly hinder the measurement. This is especially true for sensors that rely on weak, reversible interactions with the analyte. There is a clear need for the development of new molecules that can be incorporated into the transducer layers of chemical sensors and provide multiple modes of detection for more than one analyte/interferant combination and thus enhance the overall selectivity of the sensor. These dyes must also be soluble in solvents that the metal ions are likely to be present in (e.g., aqueous) or at least be in the matrix (sol−gel[9,10] or organic polymer[11,12]) in which the indicator is to be entrapped. The latter property aids the processability of the compound in terms of sensor construction.

The compounds reported here constitute the first generation of new porphyrazines (pz's) that bind metal ions and produce

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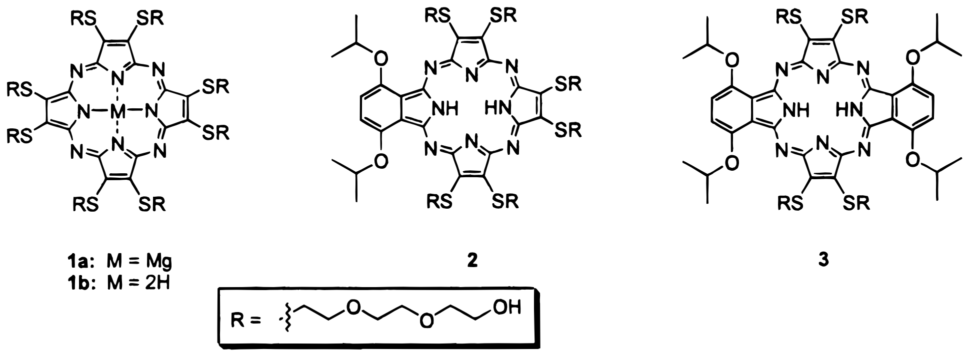

Figure 1. Polyetherol-functionalized porphyrazines.

unique optical responses for certain heavy metal cations in aqueous and alcoholic solvents. There exist many commercially available indicators that enable the quantification of metal ions in solution by colorimetric or fluorescence measurements. Particularly low detection limits may be achieved by colorimetric means when the metal chelator has a large molar extinction coefficient. Chelator emission is also a property of interest because fluorescence measurements have the distinct advantage of being even more sensitive than absorbance spectroscopy. For example, investigations into the selective and sensitive determination of toxic chromium (VI) ions in wastewater have focused on commercial indicators.[13] Other examples demonstrate either a fiber optic sensor or a sol–gel-modified integrated optic waveguide sensor, for heavy metal ions, using immobilized xylenol orange.[14] However, the problem of selectivity remains a concern for the majority of both of these types of ligand dyes. Recently, there has been a focus on crown ethers and macrocyclic compounds as transduction elements for selective metal-ion detection and/or -binding ionophores.[15–22] However, such compounds do not allow for optical transduction in the visible region without the attachment of a fluorescent chromophore. The present results open the possibility that the peripherally substituted porphyrazines can be developed into ion-selective sensors with favorable intrinsic absorption and luminesence properties.

Experimental Section

Synthesis. Bis(disodium)maleonitriledithiolate (Na_2MNT)[23] and 4,7-diisopropyloxy-1,3-diiminoisoindoline, **5**,[5] were prepared according to literature procedures. All other reagents were obtained from Aldrich Chemical Co. and used without purification. ^1H and ^{13}C NMR spectra were obtained on a Varian Gemini 300 MHz instrument. Mass spectrometry was performed by the Northwestern University Analytical Services Laboratory. Routine UV–visible spectra were obtained on a Hewlett-Packard 8452A diode array spectrophotometer.

Bis{2-[2-(2-hydroxyethoxy)ethoxy]ethylthio}maleonitrile (4). To a suspension of disodium dithiomaleonitrile, Na_2MNT (6.09 g; 32.7 mmol), in acetone (140 mL) was added 2-[2-(2-chloroethoxy)ethoxy]-ethanol (9.8 mL; 67 mmol) and NaI (ca. 1 g). The reaction was stirred at reflux under a nitrogen atmosphere for 18 h. The solvent was then removed under reduced pressure. The residue was dissolved in $CHCl_3$ and filtered to remove NaCl, NaI, and unreacted Na_2MNT. Pure **4** was obtained as a viscous yellow oil following column chromatography over silica (5–10% $CH_3OH/CHCl_3$, eluent). Yield: 7.18 g (54%). ^1H NMR δ ($CDCl_3$): 2.86 (br s, 2H), 3.28 (t, 4H), 3.52–3.74 (m, 20H). ^{13}C NMR δ ($CDCl_3$): 34.35, 61.18, 69.04, 69.81, 70.20, 72.15, 111.82, 120.92. FAB MS *m*/*z*: 407 ($M + H^+$), 429 ($M + Na^+$). Anal. Calcd for $C_{16}H_{26}N_2O_6S_2$: C, 47.28; H, 6.45; N, 6.90. Found: C, 47.32; H, 6.57; N, 6.84.

[Mg] 2,3,7,8,12,13,17,18-Octakis{2-[2-(2-hydroxyethoxy)ethoxy]-ethylthio}porphyrazine (1a). Magnesium turnings (22 mg; 0.91 mmol) were suspended in 1-butanol (6 mL). After the suspension was heated to reflux under a nitrogen atmosphere, a chip of iodine was added to initiate the formation of $Mg(OBu)_2$. Once all of the Mg had reacted (ca. 24 h), bis{2-[2-(2-hydroxyethoxy)ethoxy]ethylthio}maleonitrile, **4** (1.0 g; 2.5 mmol), was added to the $Mg(OBu)_2$/butanol suspension. A yellow precipitate formed immediately. The yellow color persisted for over 1 h and then gradually turned green. After 3 h, the reaction mixture was a deep-blue color. Heating and stirring were continued for a total of 24 h after which the solvent was removed in vacuo. The residue was dissolved in a 15:85 methanol/chloroform solution, filtered through $MgSO_4$, concentrated, and chromatographed over silica (10% $CH_3OH/CHCl_3$, eluent). Pure **1a** was isolated as a blue semisolid. ^1H NMR δ ($CDCl_3$): 2.00 (br s, 8 H), 3.14 (m, 32 H), 3.38 (t, 16 H), 3.56 (t, 16 H), 3.98 (t, 16 H), 4.31 (t, 16 H). UV–vis (H_2O) λ_{max}, nm: 372, 502, 668. FAB MS *m*/*z*: 1649 ($M + H^+$), 1671 ($M + Na^+$).

[2H] 2,3,7,8,12,13,17,18-Octakis{2-[2-(2-hydroxyethoxy)ethoxy]-ethylthio}porphyrazine (1b). Compound **1a** was dissolved in CF_3COOH (TFA, 15 mL) and placed in the dark overnight. The TFA was then removed in vacuo, and the remaining solid was neutralized by the careful addition of concentrated $NH_4OH_{(aq)}$. After the removal of water in vacuo and chromatography over silica (10%, $CH_3OH/CHCl_3$, eluent), the free-base porphyrazine **1b** was obtained in 18% yield, based on **4**. ^1H NMR δ ($CDCl_3$): −2.28 (br s, 2 H), 2.13 (br s, 8 H), 3.44 (t, 16 H), 3.57 (m, 32 H), 3.66 (t, 16 H), 4.00 (t, 16 H), 4.26 (t, 16 H). UV–vis (CH_2Cl_2) λ_{max}, nm (log ϵ): 336 (4.64), 506 (4.26), 630 (4.26), 710 (4.15). FAB MS *m*/*z*: 1628 ($M + H^+$), 1651 ($M + Na^+$). Anal. Calcd for $C_{64}H_{106}N_8O_{24}S_8$: C, 47.22; H, 6.56; N, 6.88. Found: C, 47.02; H, 6.59; N,6.67.

Porphyrazine Hybrids (1b, 2, and 3). Magnesium turnings (0.108 mg, 4.5 mmol) were added to 1-butanol (30 mL), and the suspension was refluxed under nitrogen until all of the magnesium was converted to $Mg(OBu)_2$ (ca. 24 h). The solution was cooled to 100 °C, at which time dinitriles **4** (2.44 g; 6.0 mmol) and **5** (2.35 g; 9.0 mmol) were added. The solution was stirred at 100 °C for 5 h, during which time the solution went from orange to blue-black. The solvent was removed in vacuo, the residue was dissolved in CH_2Cl_2 (10 mL), and TFA (5 mL) was added. After being stirred for 20 min, the reaction mixture was poured over ice and neutralized with excess $NH_4OH_{(aq)}$. The resulting layers were separated, and the aqueous layer was extracted

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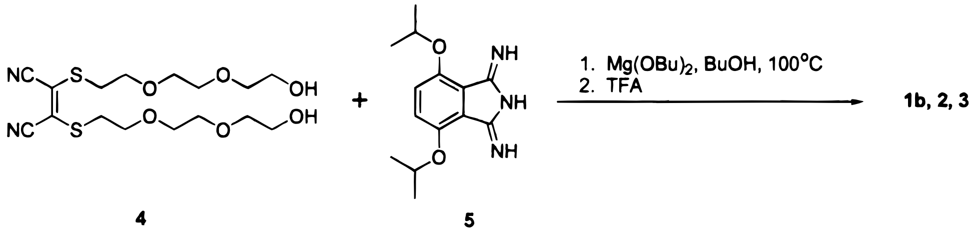
Scheme 1. One-Pot Synthesis of Polyetherol-Functionalized Porphyrazines **1b**, **2**, and **3**



with CH_2Cl_2 until the washings were colorless. The CH_2Cl_2 fractions were combined and dried over Na_2SO_4, and the solvents were removed under reduced pressure. The solid residue was chromatographed over silica gel (5% MeOH in $CHCl_3$ eluent) to yield three pigments in the order **3**, **2**, and **1b**. Pigments were further purified using eluents as follows.

[2H] 2,3,7,8,12,13,17,18-Octakis{2-[2-(2-hydroxyethoxy)ethoxy]-ethylthio}porphyrazine (1b). Chromatographed over silica gel (8% MeOH in $CHCl_3$ eluent) to yield pz **1b**. Spectroscopic data were in agreement with the compound isolated above.

3:1-Sulfurpolyetherol Porphyrazine (2). Chromatographed over silica gel (6% MeOH in $CHCl_3$ eluent) to yield **2**. ^1H NMR (300 MHz, $CDCl_3$): δ −0.17 (br s, 2H), 1.82 (d, 12 H), 3.31−4.36 (m, 72 H), 5.28 (hp, 2 H). UV−vis (CH_2Cl_2) λ_{max}, nm: 354, 654 (sh), 702, 743 (sh). FAB MS *m/z*: 1466 ($M + 2H^+$).

***trans*-Sulfurpolyetherol Porphyrazine (3).** Chromatographed over silica gel (3% MeOH in $CHCl_3$ eluent) and subsequently over alumina (1% MeOH in $CHCl_3$ eluent) to yield **3**. ^1H NMR (300 MHz, $CDCl_3$): δ −0.43 (br s, 2 H), 1.81 (d, 24 H), 3.30−3.83 (m, 40 H), 4.36 (t, 8 H), 5.28 (hp, 4 H), 7.56 (s, 4 H). UV−vis (CH_2Cl_2) λ_{max}, nm (log ϵ): 343 (4.64), 656 (4.67), 794 (4.54). FAB MS *m/z*: 1306 ($M + H^+$). Anal. Calcd for $C_{60}H_{86}N_8O_{16}S_4 \cdot H_2O$: C 54.52, H 6.72, N 8.48. Found: C 54.49, H 6.61, N 8.57.

Metal Ion Binding. The effect of metal ions on the native absorbance and emission spectra of compounds **1**−**3** were monitored using a Hitachi U-2000 double-beam absorbance spectrophotometer and an Instruments S.A. FluoroMax-2 spectrofluorometer. The test salts used as cation sources [$AgNO_3$, $Pb(NO_3)_2$, $Cd(NO_3)_2 \cdot 4H_2O$, CsCl, and $NiCl_2 \cdot 6H_2O$] were obtained from Aldrich Chemical Co. and used as purchased. Spectra were obtained using 100% ethanol (Quantum Chemical Co.) as solvent, with the exception of reactions with CsCl and $Cd(NO_3)_2 \cdot 4H_2O$, where a 10% v/v mixture of water and ethanol was used to ensure complete dissolution of the analyte salts.

Stock ethanol solutions of **1b** (40 μM), **2** (240 μM), and **3** (150 μM) were prepared and their absorption spectra recorded (0.1 cm quartz cuvettes). Each stock solution was then treated with enough $AgNO_3$ to create an essentially saturated solution, and the absorbance spectra were recorded. This procedure was then repeated for each of the other metal salts. The absorbance responses of Mg-centered **1a** to the above cations were similarly investigated to observe the effects of occupation of the internal macrocyclic cavity on the optical changes caused by peripheral metal-ion binding.

Porphyrazine stock solutions containing 60 ppm (37 μM) of **1b**, 33 ppm (23 μM) of **2**, and 9 ppm (7 μM) of **3** were prepared, their emission spectra obtained by exciting at 350 nm (compounds **1b** and **2**) or 340 nm (**3**), and recording observed emission from 400 to 900 nm. The measurements were then repeated on separate pz solutions containing large stoichiometric excesses of metal cations, as described above.

In a separate experiment, silver ions ($AgNO_3$) were added in 41−42 μM increments to a (42 μM) solution of **1b** in water, and the progressive changes in the spectrum monitored. The experiment was then repeated with a 23 μM solution of **3**. Similar experiments were performed using ethanol solutions of **1a** and **3** and titrating with cadmium ions.

Results

The reaction of disodium maleonitriledithiolate (Na_2MNT)[23] with 2-[2-(2-chloroethoxy)ethoxy]ethanol and NaI catalyst in refluxing acetone affords bis{2-[2-(2-hydroxyethoxy)ethoxy]-ethylthio}maleonitrile, **4**, in moderate yield. Subsequent macrocyclization with magnesium butoxide in refluxing 1-butanol[24,25] gives the new pigment [Mg] octakis[(hydroxyethoxy)-ethoxy]ethylthioporphyrazine, **1a**. Removal of the magnesium ion was accomplished by treatment with trifluoroacetic acid, and the free-base porphyrazine **1b** was purified by column chromatography. Compound **4** was also cocyclized with 4,7-diisopropyloxy-1,3-diiminoisoindoline, **5**, in a 2:3 stoichiometry to give the unsymmetrical porphyrazines **2** and **3**, along with **1b**, following treatment with trifluoroacetic acid and separation by column chromatography (Scheme 1).

The appended polyetherol moieties greatly enhance the porphyrazines' solubilities. All three pigments are freely soluble in common organic and alcoholic solvents and show no evidence of aggregation or self-quenching when luminescent. As expected, their solubility in aqueous media increases with the number of peripheral polyetherol arms. Compounds **1** (**a** and **b**) and **2**, with eight and six polyetherol arms, respectively, are freely soluble in water. In particular **1** has the remarkable property of showing a partition coefficient of ca. 1:5 between water and chloroform. Compound **3**, with four arms, is not water-soluble but is freely soluble in a mixture of 3:7 ethanol/water.

Optical Properties. The absorption spectrum of **1a** in ethanol is typical of porphyrazines of D_{4h} symmetry, with a single Soret transition at 365 nm, a Q-band transition at 664 nm, and a shoulder at ca. 630 nm. The absorption spectra of the free-base pigments **1b**, **2**, and **3** in ethanol are shown in Figures 2, 3 and 4, respectively, and are consistent with those observed for porphyrazines with lowered molecular symmetry.[6,7] Each spectrum shows one intense, slightly broadened Soret transition between 330 and 360 nm, as well as split Q-band transitions between 600 and 800 nm, the splitting brought about by the loss of degeneracy of the lowest unoccupied molecular orbitals (LUMO's). The Q-band region is distinctive for each molecule, with the absorbance spectrum of the trans macrocycle **3** in particular displaying a remarkably large splitting of the Q-band, whose components appear at 656 and 794 nm (Figure 4). The spectrum of each macrocycle also shows a broad band of lesser intensity between 400 and 550 nm. These bands are not seen in alkyl-substituted pz's, and their intensities increase with the number of thioether substituents. They are therefore assigned to S(n) → π^* transitions. In spectra of aqueous solutions, the Q-band region for both **1b** and **2** is significantly broadened and shifted toward shorter wavelength. The effect is most evident for **1b**, with maximum Q-band absorbance at 635 nm and a visible shoulder at 713 nm. Similarly, the spectrum of **2** in water shows a greatly broadened Q-band centered at 670 nm. These results we attribute to aggregation of the hydrophobic pz core.

Phthalocyanines are well-known to exhibit fluorescence emission from their first (S_1) and second (S_2) singlet excited

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1b

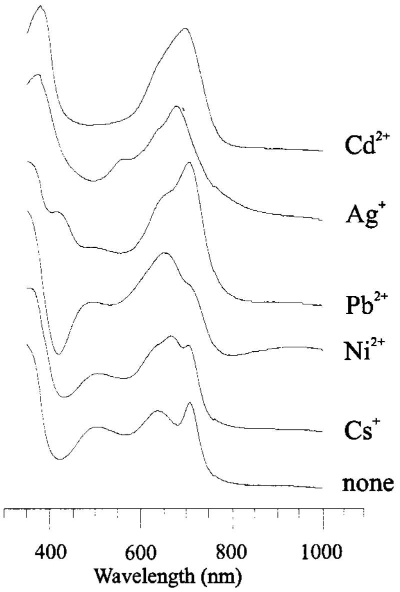

Figure 2. UV−visible absorption spectra of **1b** in ethanol (40 μM, 0.1 cm cuvette), responses to excess metal cations.

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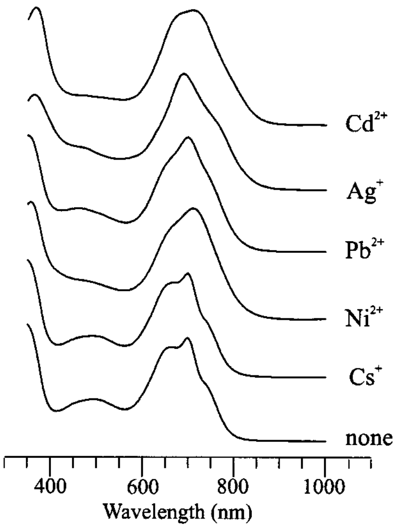

Figure 3. UV−visible absorption spectra of **2** in ethanol (240 μM, 0.1 cm cuvette), responses to excess metal cations.

states.[26] We find dual fluorescence for the pz's as well but with the intensity of the S_1 transition decreasing significantly as the number of appended sulfur atoms increases. When **1b** is excited at 350 nm, S_2 emission is observed at 409 nm (Figure 5) and very weak S_1 emission (not shown) at 745 nm. Excitation of **2** at 350 nm gives S_2 emission at 440 nm and S_1 emission at 780 nm (Figure 6). When excited at 340 nm, **3** emits strongly from S_2 at 424 nm and from S_1 at 823 nm (Figure 7); excitation at wavelengths beyond ca. 400 nm gives only S_1 emission. The weakening of S_1 emission with the number of appended sulfur atoms suggests that the S_1 excited state rapidly decays through radiationless conversion to sulfur (n, π^*) states and these to the ground state.

Interaction with Metal Ions. The response of the UV−visible absorbance spectra of **1b**, **2**, and **3** to the presence of a large molar excess of a variety of metal cations (Ag^+, Pb^{2+}, Cd^{2+}, Cs^+, Ni^{2+}) is shown in Figures 2−4. Each study was performed using ethanol as solvent with the exception of reactions with CsCl and $Cd(NO_3)_2 \cdot 4H_2O$, where a 10% v/v mixture of water and ethanol was used to ensure complete dissolution of the analyte salts. The small amount of added water had no effect on the spectra of the macrocycles in the absence of the analyte salts.

3

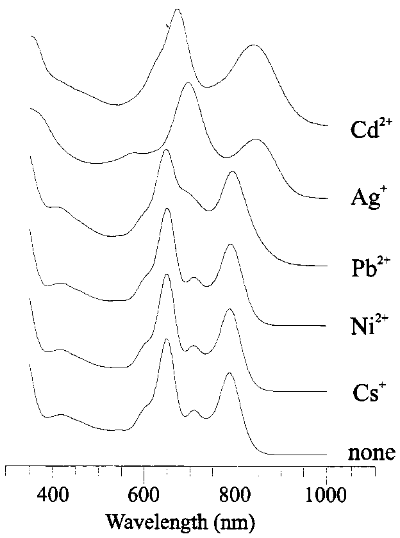

Figure 4. UV−visible absorption spectra of **3** in ethanol (150 μM, 0.1 cm cuvette), responses to excess metal cations.

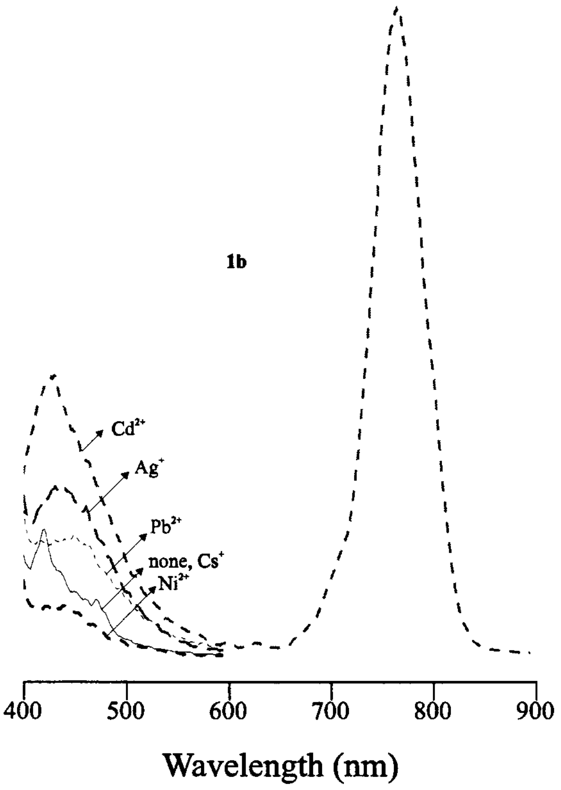

Figure 5. Fluorescence emission spectra of **1b** in ethanol (37 μM, 350 nm excitation), responses to excess metal cations.

The pigments **1b**, **2**, and **3** exhibit distinct spectroscopic changes that vary significantly with the analyte cation. For each macrocycle, the most distinct optical changes are observed upon treatment with Cd^{2+} and Ag^+. This is particularly evident for **3**

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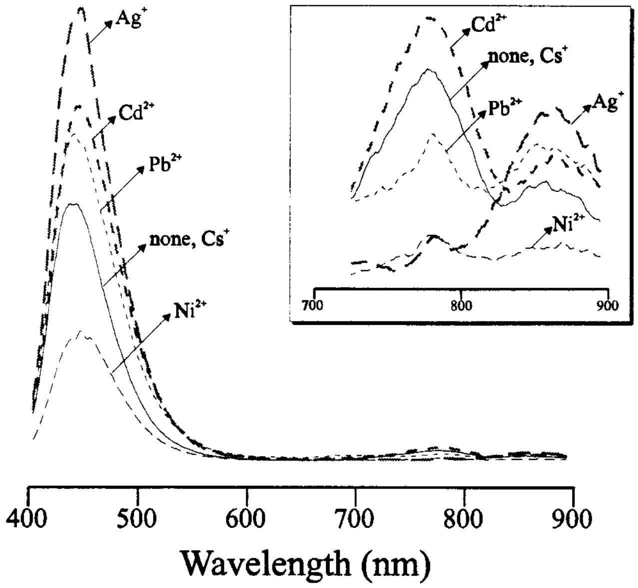

Figure 6. Fluorescence emission spectra of **2** in ethanol (23 μM, 350 nm excitation), responses to excess metal cations. Inset: S_1 emissions for the same cations.

3

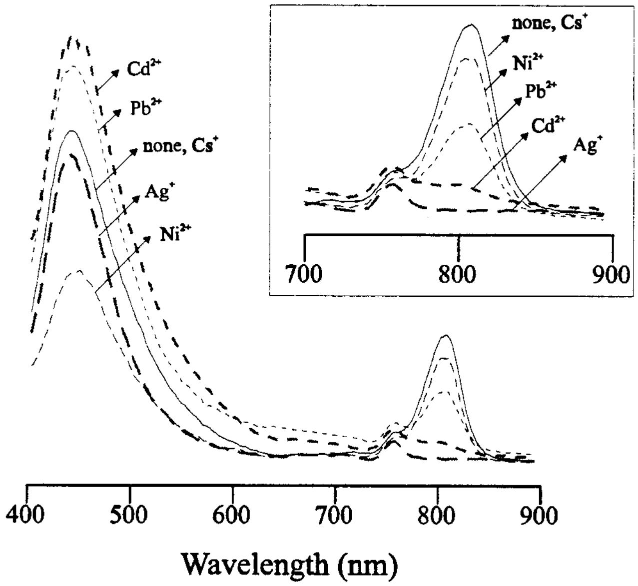

Figure 7. Fluorescence emission spectra of **3** in ethanol (7 μM, 340 nm excitation), responses to excess metal cations. Inset: S_1 emissions for the same cations.

(Figure 4), where treatment of the pz with both Cd^{2+} and Ag^+ results in a clear broadening and shift to higher wavelength of the observed Q-bands. There is also a notable decrease in the intensities of the S(n) $\rightarrow$ π^* transitions for each pz in the presence of these metal ions, which indicates coordination to the peripheral sulfur atoms.[4,27] For **1b** (Figure 2) and **2** (Figure 3), treatment with Pb^{2+} or Ni^{2+} also produces observable changes in the Q-band region. Compound **3** shows only very subtle changes when treated with Pb^{2+} and no observable change when treated with Ni^{2+}. Treatment of each pz with Cs^+ brought about the least amount of spectral changes; only very subtle differences are observed for **1b** and virtually none for **2** or **3**.

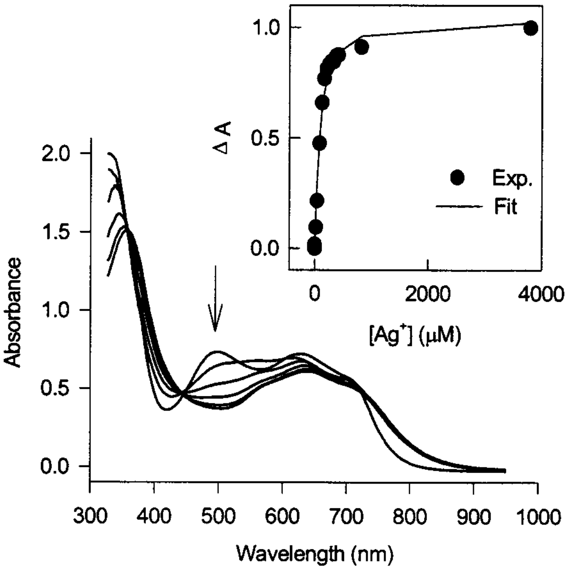

Figure 8. Absorbance spectra of **1b** (42 μM in water) as a function of silver ion concentration. Spectra represent the addition of 0, 42, 83, 125, 167, and 208 μM Ag^+. Arrow indicates an overall loss in absorbance with increasing metal-ion concentration at the selected wavelength of 496 nm. Inset: Plot of relative absorbance changes as a function of $[Ag^+]$.

The fluorescence spectra of **1b**, **2**, and **3** exhibit distinct changes in the intensities of the S_1 and S_2 emissions upon treatment with excess metal cations. In the presence of Cd^{2+} and Ag^+ **1b** shows an increase in the intensity of the S_2 emission while Pb^{2+} and Cs^+ have virtually no effect on emission intensity (although a small shift to higher wavelength is observed for Pb^{2+}) and Ni^{2+} has a quenching effect (Figure 5). An increase in S_1 emission is especially large in the presence of Cd^{2+}. For **2**, S_2 emission is increased in the presence of Cd^{2+}, Ag^+, and Pb^{2+}, while Cs^+ again has no effect and Ni^{2+} reduces the intensity of emission (Figure 6). Emission at S_1 is again increased by the addition of Cd^{2+}, though the effect is slight (far less dramatic than that observed for **1b**); it is shifted to longer wavelength by addition of Ag^+. Changes are most easily observed for **3** (Figure 7), where the addition of Cd^{2+} and Pb^{2+} again increases emission intensity at S_2 while Cs^+ has no effect, and Ag^+ and Ni^{2+} both reduce emission intensity. Each cation reduces the intensity of the S_1 emission of **3**.

To estimate the metal-ion affinity of **1b**, a solution of **1b** in water was titrated with Ag^+, and changes in the optical spectra vs $[Ag^+]$ were monitored. As depicted in Figure 8, although the titration shows apparent isosbestic points at ~350 and ~445 nm, there is clearly nonisosbectic behavior between ~500 and 700 nm. This indicates that multiple metal ions bind to the pz in a sequential fashion. Nonetheless, the absorbance decreases at 496 nm, where the response to metal-ion binding is best measured, are rather well described by a fit to an average 1:1 binding isotherm, which gives a dissociation constant of $K_D \approx$ 60 μM.

Titration of an ethanol solution of **3** with Ag^+ gave similar results, with isosbestic behavior at ~355 and ~660 nm (Figure 9). Here, a plot of the absorbance at 656 nm in response to metal-ion concentration, shown in the inset, gives a dissociation constant of $K_D = 8$ μM when fit to an average 1:1 binding isotherm. Figure 10 demonstrates a similar addition of Cd^{2+} ions to compound **3** in ethanol. The affinity of compound **3** for cadmium ions is much smaller than that for silver ions, with a fit of the data to a 1:1 isotherm requiring that $K_D \geq 500$ μM.

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(27) Doppelt, P.; Huille, S. *New J. Chem.* **1990**, *14*, 607−609.

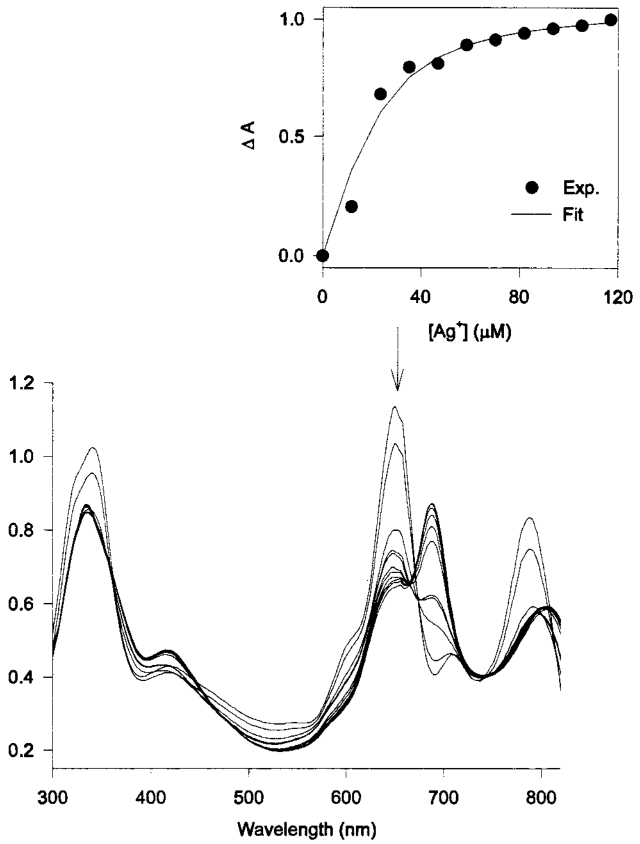

Figure 9. Absorbance spectra of compound **3** (23 μM in ethanol) as a function of silver ion concentration. Spectra represent the addition of 0, 12, 23, 35, 46, 58, 70, 82, 94, 105, and 117 μM Ag^{2+}. Arrow indicates an overall loss in absorbance with increasing metal-ion concentration at the selected wavelength of 656 nm. Inset: Plot of relative absorbance changes at 656 nm as a function of [Ag^+].

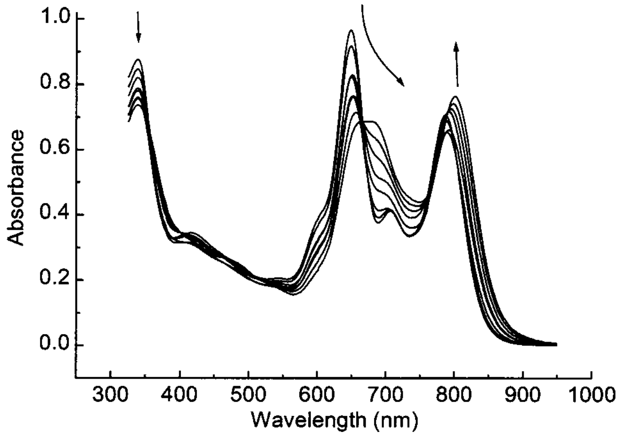

Figure 10. Absorbance spectra of compound **3** (4.1 μM in ethanol) as a function of cadmium ion concentration. Spectra represent the addition of 81, 159, 306, 630, 902, 1136, 1338, and 1515 μM Cd^{2+}. Arrows indicate trends in peak shape/position with increasing metal-ion concentration.

To probe the effect of a central metal ion on the ability of the porphyrazines to bind peripheral metal ions, a solution of the [Mg] pz **1a**, was titrated with Cd^{2+}, and changes in the optical spectra were monitored, as before (Figure 11). Only upon the addition of >600 μM Cd^{2+} to a micromolar solution of the pigment was a 30% decrease in absorbance at 668 nm seen, along with the disappearance of the S(n) → π* transition between 450 and 500 nm. This suggests that the Mg center inhibits the ability of the macrocycle to optically transduce the binding of metal ions. It appears that having a central metal atom, such as Mg, creates sufficient symmetry in the molecule to render ineffective (at changing the absorbance spectrum) the interactions of metal ions (such as Cd^{2+}) with the peripheral groups of the pz. It is also possible that the electron-withdrawing effect of the central metal ion sufficiently reduces the donating ability of the peripheral sulfur atoms to render them ineffective as metal binders.

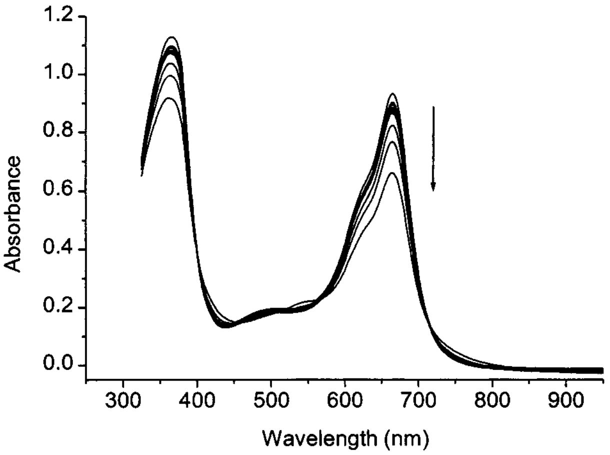

Figure 11. Absorbance spectra of **1a** in water as a function of cadmium ion concentration. Arrow indicates an overall loss in absorbance with increasing metal-ion concentration at the selected wavelength.

Discussion

We have prepared porphyrazines funtionalized with peripheral bis[thioethoxy(ethoxy)ethanol] groups and examined their ability to bind metal ions at the periphery. Each of **1b**, **2**, and **3** shows responses to the binding of a diverse set of metal ions, with **1b** showing the biggest changes in spectra over the widest wavelength range. Selectivity of peripheral metal-ion binding appears to increase as the number of peripheral polyetherol side chains is decreased, as evidenced by the observation that clear changes in the spectrum of **3** were observed only upon treatment with Cd^{2+}, Ag^+, and, to a much lesser extent, Pb^{2+}, while distinct changes in the optical spectrum of **1b** were seen upon treatment with each metal ion tested. Most of the metal-ion-pigment binding interactions are thought to involve interactions at the periphery, as evidenced by the disappearance of the S(n) → π* transitions in the optical spectra and the continued optical responses even at high metal-ion concentrations. However, the presence of a central metal ion (Mg^{2+}) appears to have a detrimental effect on the ion-sensitive spectroscopy of these compounds.

The values for the dissociation constants are rather low relative to those needed for complete separation of metal ions and/or their quantitative analysis. They do, however, appear to lie within the range desired for transducer layer molecules in optically based chemical sensors, where high sensitivity to small optical changes is easily obtained and small formation constants can be tolerated and ensure reversible sensor responses.[7,8,15−17]

The selectivity of the analyte−indicator interactions, as evidenced by the differences between individual spectra, and the increased solubility in protic media make these molecules intriguing candidates for use in the transducer layers in optical sensors. Furthermore, the demonstrated tailorability of the chelation and optical properties of these macrocycles offers insight into the realm of porphyrazine peripheral modification for our “next-generation” materials that will have more fully optimized metal-binding characteristics.

Conclusions

The peripherally modified porphyrazines synthesized and spectroscopically investigated in this work represent a unique class of selective metal-ion chelators that absorb/emit in the visible region. Solubility in polar media (alcohols and water) aids the quantification of the metal−macrocycle interactions in solution. The ease of tailoring of the chemical and spectroscopic properties of these pz’s through side-group variation allows continuing studies to focus on the development of a next generation of indicator compounds for the targeting of particular metal cations with similar selectivity characteristics but greater sensitivity.

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