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Carbamate-appended Zn–porphyrin: a neutral receptor for anions

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Abstract

A new neutral anion receptor that contains a unique combination of an immobilized Lewis acidic binding site and carbamate groups enabling additional hydrogen bonds with a coordinated anion guest has been developed. UV–vis titration binding studies revealed the free-base porphyrin **1** and ZnTPP to be poor complexing agents for anions. In contrast, the zinc metalloporphyrin receptor **2** strongly bound anionic guests and selectivity trends turned out to be dependent upon the anion basicity and geometrical complementarity between **2** and the guest. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: anion recognition; hydrogen bonding; metal–ligand interaction; Zn-porphyrin; carbamate.

Compared to the relatively well-developed cation receptors,[1] development of anion-binding agents[2] has only recently attracted attention due to its biomedical[3] and environmental significance.[4] In biological systems, the selective binding of phosphate and sulfate often takes place by a combination of hydrogen bonds and Lewis acidic metal coordination.[5] By far, the basic strategy for the construction of anion-binding receptors is to exploit electrostatic interactions[6] and/or hydrogen bonds,[7] or Lewis acidic metal–ligand interactions.[8] Among those non-covalent interactions, we have been interested in developing neutral anion receptors using cooperative force of both the coordination to metal and multiple hydrogen bonds. The combination of axial binding on metalated porphyrins and peripheral H-bonding interactions has led to the recognition of carbohydrates and amino acids.[9] We used a porphyrin skeleton as a rigid spacer for the four hydrogen bond donors to be predisposed on favorable positions for anion binding above a porphyrin plane. Herein, we report the complexation behavior for anions of a neutral receptor **2** that contains both a Lewis acidic binding site and four additional carbamate NH groups.

The synthesis of 5,10,15,20-*meso*-tetrakis(*o*-aminophenyl)porphyrin (H_2TAPP atropisomers) was accomplished by the Collman's method.[10] The carbamate-appended porphyrin **1**[11] was prepared (80% yield) by the addition of excess ethyl chloroformate and pyridine to the THF–acetone solution of the α,α,α,α-atropisomer of H_2TAPP which was obtained by the Lindsey's

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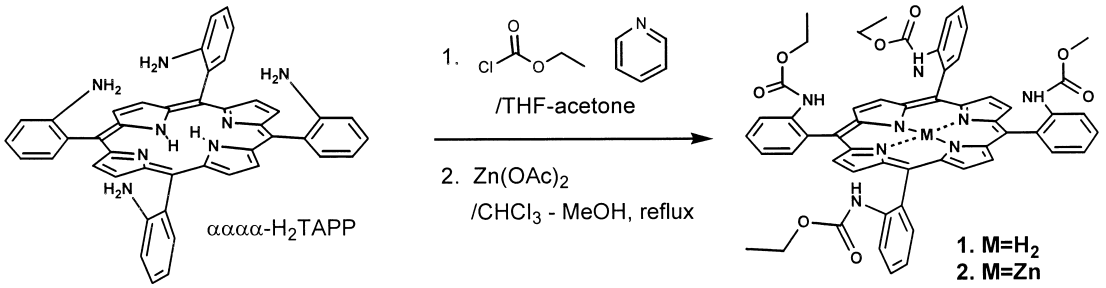
atropisomerization method.[12] Zn–porphyrin **2**[13] was prepared in quantitative yield by refluxing free-base porphyrin **1** with $Zn(OAc)_2$ in a mixture of chloroform and methanol (Scheme 1). The model Zn–tetraphenylporphyrin (ZnTPP) was prepared by standard literature procedure.[14]



Scheme 1.

UV–vis absorption experiments in chloroform stabilized by ~1% ethanol at rt showed that the Soret band of **2** underwent a red shift as a phosphate anion was bound (Fig. 1).[15] Complexation with a series of anions except I^- and HSO_4^- resulted in similar tendencies of red shifts in the Soret band. Clear isosbestic points were observed, which means the existence of two states through the formation of 1:1 complex. And, in the negative FAB mass spectrum, only 1:1 $[H_2PO_4$+**2**$]^-$ complex signal was observed. The UV–vis titration of various anions under the same condition gave the similar results. The apparent association constants for the formation of complexes between **2** and various anions were calculated by fitting the binding curve of absorbance at λ_{max} as a function of change in anion concentration. Since it was expected that the Lewis acidic Zn(II) might function as an additional anion-binding site orthogonal to the carbamate hydrogens and thus increase the overall binding strength of **2**, the association constants for **1** with only H-bonding sites and

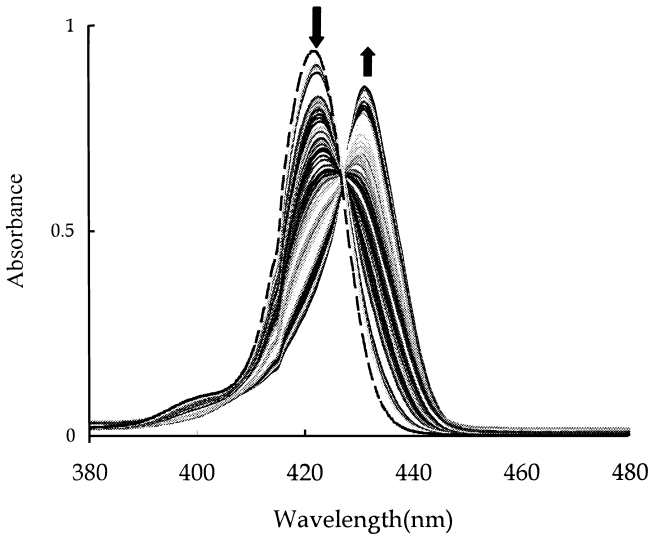


Figure 1. UV–vis titration of **2** with $H_2PO_4^-$ nBu$_4$N$^+$ in chloroform stabilized by ~1% ethanol. [**2**] = 2.0×10^{-6} M constant, $[H_2PO_4^-]$ = 0 equiv. – 2400 equiv. of **2**

ZnTPP with only Lewis acidic binding site were also measured for a comparison with those for **2** (Table 1). In the ^{31}P NMR spectra, the addition of aliquots of $CDCl_3$ solution of **2** to 40 mM *n*-$Bu_4N^+H_2PO_4^-$ in $CDCl_3$ at rt induced the ^{31}P signal of phosphate to move far upfield ($\Delta\delta = 12.25$ ppm) in comparison with free phosphate, though the phosphate binding to the Zn(II) would result in the downfield shift of the phosphate ^{31}P, implying that the bound phosphate should be placed on the shielding region of the porphyrin surface (Fig. 2).

Table 1
Association constants (M^{-1}) for porphyrins **1**, **2**, and ZnTPP and anions in $CHCl_3$/EtOH (~99:1)[a]

	F^-	Cl^-	Br^-	I^-	N_3^-	HSO_4^-	$H_2PO_4^-$	CH_3COO^-	NO_3^-
1	NB[b]	NB	NB	NB	NB	NB	NB	NB	NB
2	2.6×10^4	630	30	NB	8.6×10^3	NB	2.2×10^4	3.3×10^3	10
ZnTPP	770	30	NB	NB	70	NB	NB	15	NB

[a] Association constants were determined from UV-vis absorbance titration measurements at ambient temperature. The anions were added as their tetrabutylammonium salts except for Cl^-, which was used as tetraethylammonium salt. [b] No binding.

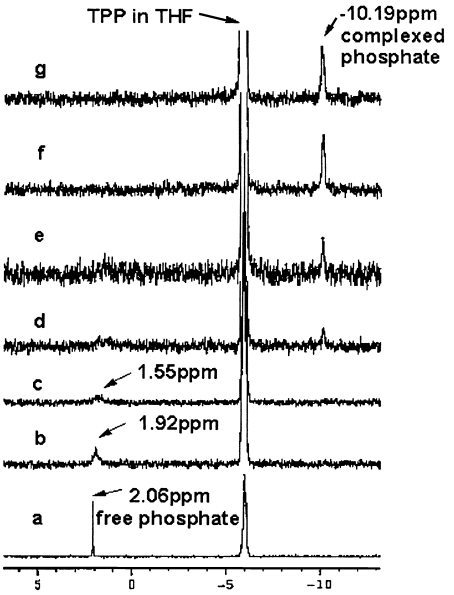


Figure 2. The change of ^{31}P signal at NMR titration of $H_2PO_4^-$ nBu_4N^+ with **2** in $CDCl_3$; (a) 40 mM $H_2PO_4^-$ nBu_4N^+ in $CDCl_3$, (b) 0.2 equiv., (c) 0.4 equiv., (d) 0.6 equiv., (e) 1 equiv., (f) 2 equiv., (g) 3 equiv. of **2**, respectively; TPP(triphenylphosphine) in THF was used as an external standard

The selectivity trends of the binding affinities of halide anions for **2** were determined to be $F^- > Cl^- > Br^- > I^-$, which were the same as for ZnTPP. This trend is due to the relative coordinating abilities of halide anions to the Zn(II) and relative hydrogen bond accepting ability of halide anions. However, the Zn(II)-free porphyrin **1** did not show binding affinities to all anions investigated, suggesting that the combination of both carbamate hydrogen bonding groups and the Lewis acid zinc metal center is essential for successful anion binding.[16] The spherical halide anions were stabilized better in the cavity of **2** with four hydrogen bond donors compared to

ZnTPP. In contrast, non-spherical anions except N_3^- with intrinsically strong coordinating power were scarcely bound to ZnTPP with the Lewis acidic center alone. The association constant of the tetrahedral bisulfate anion was smaller than that of dihydrogen phosphate with the same tetrahedral geometry, and this selectivity may be primarily due to the greater basicity of the dihydrogen phosphate anion. The association constants of acetate and phosphate anions for **2** are relatively high because of their stronger basicity, allowing them to form strong hydrogen bonds with the carbamate NHs and coordinate more strongly to the zinc metal. Though acetate is more basic than dihydrogen phosphate, the reverse trend of the binding affinity may be due to the structural preference of **2** for dihydrogen phosphate.[6e,7b] However, interestingly, the dihydrogen phosphate anion was hardly bound to both **1** and ZnTPP. This indicates that strong and selective binding for dihydrogen phosphate anion of **2** is especially effected by cooperative force of both the coordination to the zinc and hydrogen bonding interaction. In ^{1}H NMR titration of **1** with tetrabutylammonium salt of $H_2PO_4^-$ in $CDCl_3$, all proton signals of **1**, including the carbamate NH protons, were essentially not changed, but those of **2** gradually changed upon binding with dihydrogen phosphate. ^{1}H NMR titration spectra of **2** with dihydrogen phosphate showed that the β-pyrrole protons moved upfield ($\Delta\delta = -0.17$ ppm), the carbamate protons shifted upfield ($\Delta\delta = -0.46$ ppm), and the ethylene protons moved upfield ($\Delta\delta = -0.21, -0.22$ ppm). The upfield shift of the β-pyrrole protons upon complexation with dihydrogen phosphate indicated that the porphyrin ring current was decreased by the anion. The upfield shift of the carbamate NHs upon complexation indicated that the carbamate NHs were directed toward the binding pocket over the porphyrin ring and hydrogen bonded with phosphate anion coordinated to the zinc. This makes a sharp contrast to the result of Burns' urea-appended free-base porphyrins in which the urea NHs experienced downfield shifts indicative of their participation in the anion recognition process with the adjacent urea group and thus they were positioned toward the anion in the deshielding region of the porphyrin ring.[17] Especially, the peak of the complexed phosphate proton moved far upfield ($\Delta\delta = -9.06 \sim -14.0$ ppm depending on the experimental condition) appearing at –3.66 ppm, which indicated the existence of the phosphate group over the porphyrin ring by coordination of the phosphate group to the zinc metal. The proton signals of the tetrabutylammonium couterion also moved upfield, suggesting the counterion was placed over the porphyrin ring in the shielding region as an ion pair with phosphate. Complexation with N_3^- and AcO^- showed the downfield shift of the resonances of the carbamate NHs of **2** ($\Delta\delta = 0.06$ ppm for N_3^- and $\Delta\delta = 0.14$ ppm for AcO^-), indicating that hydrogen bonding interactions were involved in the anion recognition processes. However, the relatively smaller upfield shift of the carbamate NHs ($\Delta\delta = 0.02$ ppm) upon complexation with F^- seems to suggest that there are some interactions between the carbamate NHs and F^-. Since F^- coordinated to the zinc is not in the proper distance for hydrogen bonding with the carbamate NHs, we surmise that the interaction may be dipolar interaction, weaker than hydrogen bonding. It is surprising that the weak dipolar interaction contributes to 33-fold increase of the binding strength compared to binding to ZnTPP.[18]

In summary, we have developed a new neutral anion receptor that contains a unique combination of an immobilized Lewis acidic binding site (Zn(II)) and carbamate groups enabling additional hydrogen bonds with a coordinated anion guest. UV–vis anion-binding studies revealed the free-base porphyrin **1** and ZnTPP to be poor complexing agents for anions. In contrast, the zinc metalloporphyrin receptor **2** strongly bound anionic guests and selectivity trends turned out to be dependent upon the anion basicity and geometrical complementarity between **2** and the guest. For example, **2** bound phosphate anion selectively and strongly using cooperative force of both the coordination to the Lewis-acid zinc metal and multiple hydrogen bonds.

Acknowledgements

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11. Selected spectral data for **1**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.87 (s, 8H, β-pyrolic*H*), 8.60 (d, J = 8.3 Hz, 4H, meso-phenyl*H*), 8.01 (d, J = 6.9 Hz, 4H, meso-phenyl*H*), 7.87 (t, J = 7.3 Hz, 4H, meso-phenyl*H*), 7.47 (t, J = 7.4 Hz, 4H, meso-phenyl*H*), 6.23 (s, 4H, carbamate*H*), 3.80 (q, J = 7.0 Hz, 8H, OCH_2CH_3), 0.74 (t, J = 6.9 Hz, OCH_2CH_3), –2.77 (s, 2H, imide*H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 154.2, 139.6, 135.4, 132.6, 130.9, 130.6, 122.8, 120.1, 115.7, 61.5, 14.7; FAB-MS (NBA) m/z 963 ($M+H^+$); UV–vis λ_{max} (~1% ethanol–$CHCl_3$, nm) 416, 510, 543, 580.
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