Synthesis and Structures of (Porphinato)(thiolato)gallium(III) Complexes

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Gallium(III)-substituted P-450 models, [Ga(OEP)(SAr)] (OEP = octaethylporphinato; SAr = S-2-$CF_3CONHC_6H_4$, SPh), were synthesized and the structures were determined by X-ray analysis. The gallium(III) complexes were found to be excellent structural analogues having a diamagnetic metal center.

Cytochrome P-450 is a heme protein which catalyzes hydroxylation of organic compounds. The active site of substrate-bound P-450 has been known as a five-coordinated high-spin Fe(III) having a cysteine thiolato ligand (cys-peptide) at the axial position, [Fe$^{\rm III}$(porphinato)(SR)], the structure of which has been established by X-ray analysis.[1] As active site models of P-450, many (porphinato)(arenethiolato)iron(III) complexes have been synthesized and the structures were determined.[2,3] Previously, we have reported a P-450 model iron(III) complex having NH⋯S hydrogen bond, [Fe(OEP)(S-2-$CF_3CONHC_6H_4$)], and found the significant contribution of the hydrogen bond to the stabilization of the Fe$^{\rm III}$-S bond.[4]

Recently, we have synthesized novel (porphinato)(cys-peptide)iron(III) complexes having intramolecular NH⋯S hydrogen bonds and successfully realized stable Fe$^{\rm III}$-*alkanethiolate* coordination for the first time in model systems.[5] The structural determination of the iron(III) complexes using ^{1}H NMR technique is very difficult due to the presence of a paramagnetic iron(III) center (S = 5/2). In general, the replacement of the paramagnetic metal ion by a diamagnetic one is an effective technique for the structural investigation of metalloproteins. Especially Ga(III) has been known as an attractive substituent for the paramagnetic Fe(III) in iron-containing metalloproteins[6,7] because of the same charge and a similar radius.[8] Recently, Ga(III)-substituted [2Ga-2S] ferredoxin has been reported and given much more structural information than [2Fe-2S] ferredoxins.[5] On the other hand, the basic coordination chemistry about the [2Ga-2S] cluster has already been established by Koch et al.[9]

We have applied the Ga(III)-substitution to the investigation of the solution structure of the P-450 model, although such a thiolate complex, [Ga$^{\rm III}$(porphinato)(SR)], has never been reported. Here, the first synthesis and structures of Ga(III)-substituted P-450 models, [Ga(OEP)(SAr)] (SAr = S-2-$CF_3CONHC_6H_4$ (**1a**), SPh (**2a**)), are reported to develop their basic coordination chemistry. The functions of the NH⋯S hydrogen bond are also discussed.

The Ga(III) complexes, [Ga$^{\rm III}$(OEP)(SAr)], were synthesized by the reaction of [Ga$^{\rm III}$(OEP)Cl][10] with NaSAr or [Ga$^{\rm III}$(OEP)(OMe)][11] with ArSH. [Ga$^{\rm III}$(OEP)(OMe)] (20 mg, 0.031 mmol) and 2-$CF_3CONHC_6H_4SH$ (52 mg, 0.064 mmol) were dissolved and stirred in 2 mL of toluene at 70 ℃. The solution was concentrated *in vacuo* and cooled at 2 ℃ to give red crystals of **1a** in 84% yield.[12] The complex **2a** was isolated from a solution of [Ga$^{\rm III}$(OEP)Cl] (160 mg, 0.25 mmol) and NaSPh (75 mg, 0.37 mmol) in a mixture of methanol (15 mL) and CH_2Cl_2 (15 mL). After stirring for 30 min, the solvents were removed under reduced pressure. The residue was extracted with 15 mL of CH_2Cl_2 and concentrated to dryness. The crude product was recrystallized from toluene to give red-purple microcrystals of **2a** in 57% yield.[13]

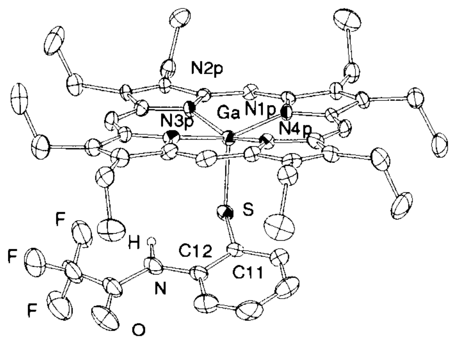

Figure 1. Molecular structure of **1a**.

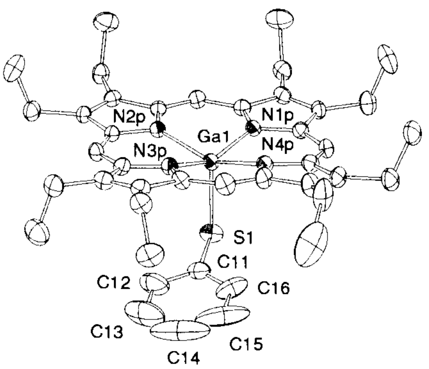

Figure 2. Molecular structure of **2a**.

Table 1. Selected bond distances (Å) and angles (degree) of [M$^{\rm III}$(OEP)(S-2-$CF_3CONHC_6H_4$)] (M = Ga (**1a**), Fe (**1b**)) and [M$^{\rm III}$(OEP)(SPh)] (M = Ga (**2a**) and Fe (**2b**))

	1a (Ga)	**1b** (Fe)[a]	**2a** (Ga)	**2b** (Fe)[b]
M-S	2.315(3)	2.327(4)	2.274(2)	2.299(3)
M-N1p	2.054(9)	2.05(1)	2.043(6)	2.052(6)
-N2p	2.022(6)	2.049(8)	2.054(5)	2.054(6)
-N3p	2.03(1)	2.04(1)	2.038(6)	2.062(6)
-N4p	2.005(7)	2.033(9)	2.044(6)	2.059(6)
mean	2.04	2.04	2.045	2.057
M-N_4	0.386	0.386	0.457	0.466
S-C	1.753(9)	1.76(1)	1.761(9)	1.766(8)
M-S-C	104.1(4)	104.0(5)	103.5(3)	102.5(3)
M-S-C-C	-103.0(9)	104(1)	93.1(9)	—

[a]Reference 4. [b]Reference 3.

The gallium complexes **1a** and **2a**[14] were crystallized in an isomorphous packing to the corresponding iron complexes, [Ga(OEP)(SAr)] (SAr = S-2-$CF_3CONHC_6H_4$ (**1b**)[4], SPh (**2b**)[3]). The molecular structures are shown in Figures 1 -2 and selected bond distances and angles are summarized in Table 1 compared with those of the iron(III) analogues. Any significant difference between **1a** and **1b** could not be found in the distances and the angles. However, significant shortening (0.025 Å) of the Ga-S bond of **2a** in comparison with the Fe-S of **2b** is considered to be caused by the difference of their ionic radii, *i.e.*, 0.69 Å and 0.72 Å for five-coordinate Ga(III) and Fe(III) ions, respectively.[8] The Ga^{III}-S bond distance has been believed to little depend on the electron-donating ability of the ligand, *e.g.*, 2.264(3) Å for $[Ga^{III}(SEt)_4]^-$ and 2.257(8) Å for $[Ga^{III}(SPh)_4]^-$. In contrast, the Fe^{III}-S bond obviously shows π-bonding character, when comparison was made between 2.269(1) Å for $[Fe^{III}(SEt)_4]^-$ and 2.297(6) Å for $[Fe^{III}(SPh)_4]^-$.[9] Among the porphinato complexes, the Ga-S bond distance depends on the identity of axial ligand which has already been known for similar iron(III) complexes.[4]

Elongation of the Ga-S bond by the NH···S hydrogen bond formation was now found. The larger difference (0.041 Å) in comparison with the iron analogue (0.028 Å) is consistent with the strength of the NH···S hydrogen bond. IR spectrum of **1a** in the solid state shows ν(NH) at 3215 cm^{-1} which is low-wavenumber-shifted than free ν(NH) (3358 cm^{-1}) of the corresponding disulfide, $(S\text{-}2\text{-}CF_3CONHC_6H_4)_2$ by 143 cm^{-1}. The shift value, *i.e.*, the strength of the hydrogen bond, is significantly larger than the shift in the complex **1b** (123 cm^{-1}).[4]

The elongation of M-S bond is due to the decrease of electron-donating ability induced by the NH···S hydrogen bond formation. This result is in contrast to the observed shortening of M-S bond for Fe(II), Cu(I), and Mo(V) thiolate complexes.[16] This phenomenon has been explained that the NH···S hydrogen bond decreases anti-bonding M(dπ)-S(pπ) character in HOMO.[16] However the porphinato complexes have no such an interaction in HOMO.[17] In the complexes **1a** and **1b**, the degree of elongation by the hydrogen bond is considered to cancel out the difference of ionic radii between Ga(III) and Fe(III).

In conclusion, a remarkable structural similarity of the Ga(III)-substituted P-450 model complex to the corresponding Fe(III) complex has been found, which demonstrates the suitability of Ga(III)-substitution in solution-structural analysis.

References and Notes

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11 Synthesis of $[Ga^{III}(OEP)(OMe)]$: A mixture of [Ga(OEP)Cl] (50 mg, 0.078 mmol) and NaOMe (11 mg, 0.2 mmol) was dissolved in 5 mL of hot methanol and concentrated under reduced pressure. The residue was extracted with CH_2Cl_2 (5 mL) and evaporated to give a crude product which was recrystallized from methanol. Yield 43 mg (79%). Anal. Found: C, 67.63; H, 7.63, N, 8.34%. Calcd for $C_{37}H_{47}N_4OGa\cdot 3/2(CH_3OH)$: C, 67.84; H, 7.84, N, 8.22%. The original crystal contains three methanol molecules as crystal solvent which is easily removed under reduced pressure.

12 **1a**: Anal. Found: C,65.11; H, 6.07; N, 8.06%. Calcd for $C_{44}H_{49}F_3GaN_5OS\cdot 1/2(C_7H_8)$: C,65.47; H, 6.14; N, 8.12%. ^1H NMR (C_6D_6): δ 1.85 (24H, t, CH_3), 3.61 (1H, d, 6-H), 3.97 (16H, m, CH_2), 5.87 (1H, t, 5-H), 6.47 (1H, t, 4-H), 7.72 (1H, d, 3-H), 6.30 (1H, s, NH), 10.26 (4H, s, *meso*-H).

13 **2a**: Anal. Found: C,71.00; H, 6.92; N, 7.87%. Calcd for $C_{42}H_{49}F_3GaN_4S$: C,70.88; H,6.94; N, 7.87%. ^1H NMR (C_6D_6): δ 1.86 (24H, t, CH_3), 4.06 (2H, d, *o*-H), 6.10 (2H, m, *m*-H), 6.45 (1H, t, *p*-H), 10.25 (4H, s, *meso*-H).

14 Crystal Data for **1a**: $C_{44}H_{49}F_3GaN_5OS\cdot 1/2(C_7H_8)$, FM = 868.75, triclinic, space group $P\bar{1}$ (No. 2), a = 13.473(5) Å, b = 14.764(5) Å, c = 12.808(3) Å, α = 103.82(2)°, β = 108.04(2)°, γ = 65.99(2)°, V = 2193(1) Å^3, Z = 2, D_c = 1.32 g cm^{-1}, μ(Mo-Kα) = 7.29 cm^{-1}, 8129 reflections collected; of these 7753 were unique, 2613 observed reflections ($I > 3.0\sigma(I)$). The structure was solved by the direct method (SHELX86).[15] R = 0.054 and R_w = 0.055, GOF = 1.43. Crystal Data for **1b**: $C_{42}H_{49}GaN_4$, FM = 711.67, triclinic, space group $P\bar{1}$ (No. 2), a = 13.189(2) Å, b = 15.049(2) Å, c = 10.365(2) Å, α = 106.79(1)°, β = 102.17(1)°, γ = 72.82(1)°, V = 1863.9(5) Å^3, Z = 2, D_c = 1.27 g cm^{-1}, μ(Mo-Kα) = 8.29 cm^{-1}, 7743 reflections collected; of these 7369 were unique, 2876 observed reflections ($I > 2.0\sigma(I)$). R = 0.050 and R_w = 0.054, GOF = 1.52.

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17 Ab initio calculation (single point energy) was performed by Wavefunction Inc. SPARTAN (ver. 4.1.2) using 3-21G$^{(*)}$ basis set. The atomic coordinates of the crystal structure of **2a** were used without further geometrical optimization. The HOMO is found to be the well-known $1a_{1u}(\pi)$ orbital without any electron density on Ga and SPh.