NMR Studies on the Isomerization of Vanadium(V)-Propylenediaminetetraacetate Complex in Solution

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In this paper we have determined the thermodynamic parameters for the isomerization between the α-*cis* and the β-*cis* isomers in vanadium(V)-propylenediaminetetraacetate complex in water by ^{51}V NMR spectroscopy. In addition, the effects of organic solvents (methanol, formamide and dimethylsulfoxide) and inorganic salts (NaCl, $NaClO_4$ and NH_4Cl) on the isomerization in solution have been investigated.

Key Words : Isomerization, ^{51}V NMR, Vanadium(V) complex, Propylenediaminetetraacetate

Introduction

Vanadium chemistry has received much attention because of its role in both inhibitory and promotory processes in various biological systems like nitrogenases,[1] haloperoxidase,[2] tunichromes[3] and several others.[4] Recently it is discovered that vanadium(V) compounds have shown the insulin mimic effect.[5,6] Vanadium complexes are particularly susceptible to external influences since the vanadium atom is small and readily accommodates several coordination geometries. Thus, understanding how various factors affect the structure and the stability of vanadium complexes is important.

Vanadium(V) forms well-characterized complexes with aminopolycarboxylate ligands, such as ethylenediaminetetraacetate (EDTA).[7-13] From X-ray crystallographic studies V-EDTA complexes have been characterized to show the vanadium atom in an octahedral geometry with a *cis*-VO_2 core.[8,9] Solution ^{1}H NMR studies show that the V-EDTA complex retains the solid state structure in solution, having α-*cis* structure.[10] In solution ethylenediaminediacetate (EDDA) ligand forms two isomers of similar stability with vanadium(V), a symmetric α-*cis* complex and an asymmetric β-*cis* complex.[10,14] In a previous paper,[15] we reported that the vanadium complex of propylenediaminetetraacetate (PDTA) ligand was determined to have α-*cis* structure in solid. The anion $[VO_2PDTA]^{3-}$ has a slightly irregular octahedral geometry in which two oxo ligands are *cis* to each other as shown in EDTA,[7,8] and EDDA complexes.[11] These two oxo oxygens have short V=O bonds which indicate strong multiple bond character. The O=V=O angle in VO_2 moiety is larger than 90° which is the standard octahedral value. The methyl group of the ethylenic backbone is located at the equatorial position in the complex. We also found from NMR studies,[15] as shown in Figure 1, that the isomerization between α-*cis* complex (1) and β-*cis* complex (2) occurrs in aqueous solution. Thus, we needed to investigate the isomerization of the EDDA complex in detail by NMR spectroscopy.

In this paper we have studied the isomerization between α-*cis* and β-*cis* isomers of vanadium(V)-propylenediaminetetraacetate (PDTA) complex in aqueous solution by ^{51}V NMR spectroscopy. In addition, we have studied the change of the isomerization with the addition of organic solvents and inorganic salts. PDTA is similar to an EDTA ligand, but PDTA has a methyl group on the ethylenic backbone in its structure, which is different from that of EDTA.

Experimental Section

Materials. All reagent grade chemicals were used as received without further purification. Ammonium metavanadate (NH_4VO_3), propylenediaminetetraacetic acid (H_4PDTA) and 25% ammonia water were obtained from Aldrich Chemical Co. Organic solvents (methanol, formamide and dimethylsulfoxide) and inorganic salts (NaCl, $NaClO_4$ and NH_4Cl) were obtained from Junsei Chemical Co.

Preparation of NMR Samples. Samples for NMR measurements were prepared by dissolving the weighed amounts of NH_4VO_3 and H_4PDTA in H_2O-D_2O (90 : 10 v/v) to give V-PDTA complex. The pH of the mixed solution was adjusted to 8.0 with ammonia solution. Organic solvents or stock solutions of inorganic salts were added in the appropriate ratios to a solution of V-PDTA complex by a 1.00 mL syringe. The final concentration of each sample was adjusted to 250 mM of the complex by addition of water.

^{51}V NMR Measurements. ^{51}V NMR specta of the complex in H_2O were recorded on a Varian Unity Inova 300WB FT NMR spectrometer at 78.897 MHz with a spectral width of 100 kHz, a pulse angle of 45°, an acquisition time of 0.1 s, a relaxation delay of 0.0 s, and approximately 1000 scans. ^{51}V chemical shifts were referenced to the external $VOCl_3$. The [α-*cis*]/[β-*cis*] ratio was determined by integration of ^{51}V NMR spectra for both isomeric complexes in solution. The overlapped ^{51}V signals were deconvoluted to individual signals before integration. The sample temperature was maintained within ± 1 °C during the measurement of spectra.

Results and Discussion

PDTA is expected as a tetradentate ligand to coordinate to VO_2^+. The remaining four coordination sites of vanadium atom are occupied by two nitrogen and two carboxylate oxygen atoms of the PDTA ligand, giving two five-membered glycinato rings in the complex. No significant changes in the ^{51}V spectra of V-PDTA complex in aqueous solution were observed in the pH range of 6 to 9. Below pH 6 the compex formation was not completed and above pH 9 the complex hydrolyzed partially.

Isomerization of Vanadium(V)-PDTA Complex in Water. PDTA ligand forms two isomeric complexes with vanadium(V), *i.e.* *α-cis* (1) and *β-cis* (2) isomers, in water as shown in Figure 1. The isomers differ in the manner in which the carboxylate is coordinated: the *α-cis* isomer has two carboxylates coordinated *trans* each other, and the *β-cis* isomer has two carboxylates coordinated *trans* to an oxo and an amine functionality. The ^{51}V NMR spectrum of vanadium-PDTA complex at ambient temperature in water shows two signals with an intensity ratio of 1.58 : 1 at -503.5 and -515.5 ppm as shown in Figure 2, indicating a mixture of two isomers. The careful analysis of ^{1}H and COSY 2D NMR spectra allowed unambiguous assignment of the resonance at -503.5 ppm to the *α-cis* isomer and at -515.5 ppm to *β-cis* isomer. The equilibrium between the *β-cis* and *α-cis* isomers is expressed by the ratio of [*α-cis*]/[*β-cis*], as shown in equation (1) and (2).

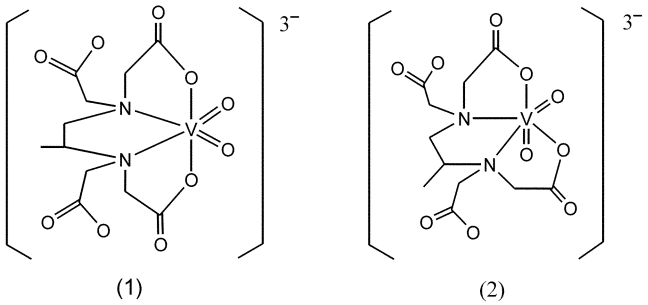

Figure 1. (1) *α-cis* and (2) *β-cis* isomers of vanadium(V)-PDTA complex.

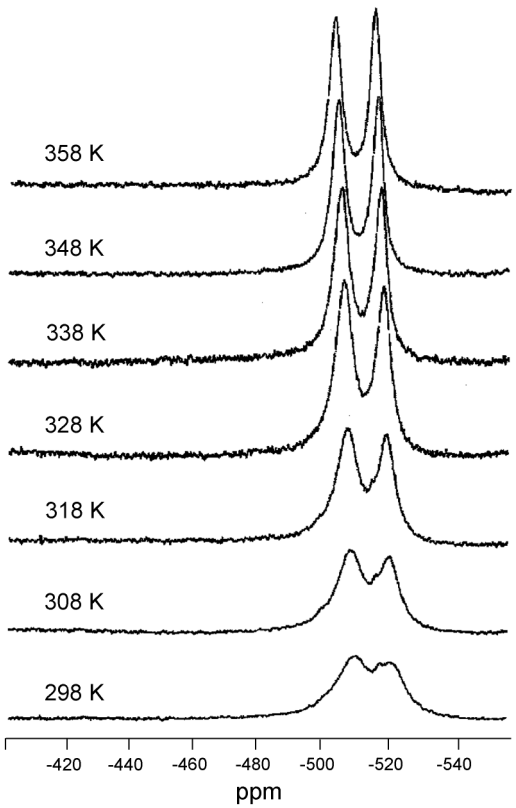

Figure 2. ^{51}V NMR spectra of V-PDTA complex in water at various temperatures.

$$\beta\text{-}cis \rightleftharpoons \alpha\text{-}cis \quad (1)$$

$$K = [\alpha\text{-}cis]/[\beta\text{-}cis] \quad (2)$$

The ^{51}V NMR spectra of vanadium-PDTA complex at various temperatures are shown in Figure 2. The ratio of [*α-cis*]/[*β-cis*] decreases as the temperature increases within the limited temperature range (298-358 K), indicating that the higher temperatures favor the *β-cis* isomer. The plot of ln K as a function of 1/T is shown in Figure 3. Analysis of the slope ($-\Delta H^o/R$) and the intercept ($\Delta S^o/R$) in the plot yields the thermodynamic parameters for the isomerization equilibrium: ΔH^o, -1.5 kcal/mol; ΔS^o, -3.9 cal/(mol K); ΔG^o_{298}, -0.34 kcal/mol. The negative ΔS^o value is consistent with the consideration that the more symmetric *α-cis* isomer has a smaller absolute entropy than the less symmetric *β-cis* isomer, assuming the similar solvation spheres of the two isomers. The small free energy difference (-0.34 kcal/mol) indicates the effect of substitution of methyl group at the ethylenic backbone in the ligand. A negligible amount of *β-cis* isomer is formed in V-EDTA complex in aqueous solution.[10] V-PDTA complex the substitution of methyl group on ethylenic backbone might increase the steric hindrance between methyl group and free acetate group bound to nitrogen in *α-cis* form and thus be likely to destabilize the *α-cis* isomer significantly.

Isomerization of Vanadium(V)-PDTA Complex in Mixed Solvent System. To examine the changes of the

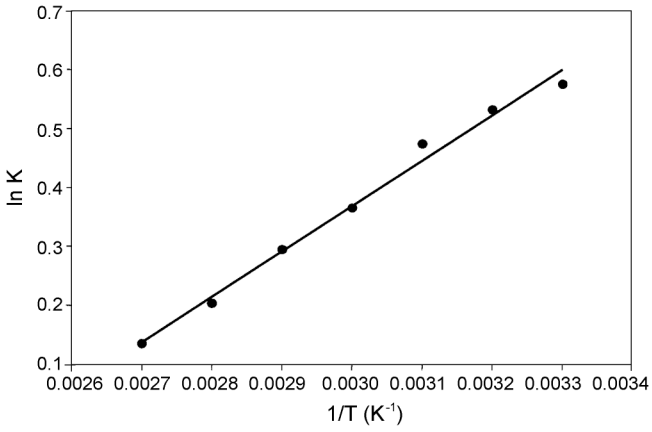

Figure 3. Plot of ln K as a function of 1/T in water.

Table 1. Ratio of [*α-cis*]/[*β-cis*] as a function of solvent composition

Solvent	Concentration (M)	[*α–cis*]/[*β-cis*]
Water		1.58
Water-Methanol	5.0	1.55
	10.0	1.52
	15.0	1.40
	20.0	1.28
Water-Formamide	5.0	1.39
	10.0	1.25
	15.0	1.21
	20.0	1.14
Water-Dimethylsulfoxide	3.0	1.33
	6.0	1.25
	9.0	1.14
	12.0	1.08

[*α-cis*]/[*β-cis*] ratio in a mixed solvent system water-organic solvent mixtures were used. Three organic solvents, methanol, formamide, and dimethylsulfoxide, were chosen because of their properties and the solubility of the complex in these solvents. The ratios of [*α-cis*]/[*β-cis*] as a function of solvent composition are shown in Table 1. As shown in Table 1, the ratio [*α-cis*]/[*β-cis*] decreases as the concentration of methanol increases. A similar effect was observed on the addition of formamide or dimethylsulfoxide. All three organic solvents show that the stability of *α-cis* isomer decreases as the amount of organic solvent increases. Dimethylsulfoxide is much more effective in destabilizing the *α-cis* isomer than methanol or formamide. The stability of *α-cis* isomer decreases in the following order: water > methanol > formamide > dimethylsulfoxide. Gutmann's scale[17] to describe the accept number (AN) decreases in the following order: water ~ methanol > formamide > dimethylsulfoxide. This is exactly the order that was observed in the stability of *α-cis* isomer. The relationship suggests that a correlation may exist with the solvents abilities to donate electron density to electron-deficient centers or accept electrons from electron-rich centers.

Table 2. Ratio of [*α-cis*]/[*β-cis*] as a function of salt concentration

Salt	Concentration (M)	[α-*cis*]/[β-*cis*]
None		1.58
NaCl	1.0	1.66
	2.0	1.75
$NaClO_4$	1.0	1.65
	2.0	1.81
NH_4Cl	1.0	1.61
	2.0	1.74

Isomerization of Vanadium(V)-PDTA Complex in Salt System. The effects of various salts in water on the ratio of [*α-cis*]/[*β-cis*] were measured, and the results are shown in Table 2. From Table 2 the addition of NaCl, $NaClO_4$ and NH_4Cl is accompanied by an increase in the [*α-cis*]/[*β-cis*] ratio. The effect by the addition of salts is similar to NaCl, $NaClO_4$ and NH_4Cl. The increased [*α-cis*]/[*β-cis*] ratio at high salt concentrations means that the stability of *α-cis* isomer increased or the stability of *β-cis* isomer decreased. If NH_4Cl is much better than NaCl in stabilizing the *α-cis* isomer, the result could be attributed to the higher ability of NH_4Cl to hydrogen bond to the *α-cis* isomer of the vanadium(V) complex. But the result shows that solvation is more important than hydrogen bonding to the [*α-cis*]/[*β-cis*] ratio in V-PDTA complex.

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