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Cobalt(III) Complexes of Monodentate N(9)-Bound Adeninate (ade^-), $[Co(ade\text{-}\kappa N^9)Cl(en)_2]^+$ (en = 1,2-Diaminoethane): Syntheses, Crystal Structures, and Protonation Behaviors of the Geometrical Isomers

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In acidic aqueous solution, a cobalt(III) complex containing monodentate N(9)-bound adeninate (ade^-), *cis*-$[Co(ade\text{-}\kappa N^9)Cl(en)_2]Cl$ (*cis*-[**1**]Cl), underwent protonation to the adeninate moiety without geometrical isomerization or decomposition of the Co^{III} coordination sphere, and complexes of *cis*-$[CoCl(Hade)(en)_2]Cl_2$ (*cis*-[**2**]Cl_2) and *cis*-$[Co(H_2ade)Cl(en)_2]Cl_3$ (*cis*-[**3**]Cl_3) could be isolated. The pK_a values of the Hade and H_2ade^+ complexes are 6.03(1) and 2.53(12), respectively, at 20 °C in 0.1 M aqueous NaCl. The single-crystal X-ray analyses of *cis*-[**2**]$Cl_2 \cdot 0.5H_2O$ and *cis*-[**3**]$Cl_2(BF_4) \cdot H_2O$ revealed that protonation took place first at the adeninate N(7) and then at the N(1) atoms to form adenine tautomer (7*H*-Hade-κN^9) and cationic adeninium (1*H*,7*H*-H_2ade^+-κN^9) complexes, respectively. On the other hand, addition of NaOH to an aqueous solution of *cis*-[**1**]Cl afforded a mixture of geometrical isomers of the hydroxo–adeninato complex, *cis*- and *trans*-$[Co(ade\text{-}\kappa N^9)(OH)(en)_2]^+$. The *trans*-isomer of chloro–adeninato complex *trans*-$[Co(ade\text{-}\kappa N^9)Cl(en)_2]BF_4$ (*trans*-[**1**]BF_4) was synthesized by a reaction of *cis*-[**2**]$(BF_4)_2$ and sodium methoxide in methanol. This isomer in acidic aqueous solution was also stable toward isomerization, affording the corresponding adenine tautomer and adeninium complexes (pK_a = 5.21(1) and 2.48(9), respectively, at 20 °C in 0.1 M aqueous NaCl). The protonated product of *trans*-$[Co(7H\text{-}Hade\text{-}\kappa N^9)Cl(en)_2](BF_4)_2 \cdot H_2O$ (*trans*-[**2**]$(BF_4)_2 \cdot H_2O$) could also be characterized by X-ray analysis. Furthermore, the hydrogen-bonding interactions of the adeninate/adenine tautomer complexes *cis*-[**1**]BF_4, *cis*-[**2**]$(BF_4)_2$, and *trans*-[**2**]$(BF_4)_2$ with 1-cyclohexyluracil in acetonitrile-d_3 were investigated by ^1H NMR spectroscopy. The crystal structure of *trans*-$[Co(ade)(H_2O)(en)_2]HPO_4 \cdot 3H_2O$, which was obtained by a reaction of *trans*-$[Co(ade)(OH)(en)_2]BF_4$ and NaH_2PO_4, was also determined.

Introduction

Transition-metal complexes with nucleobases have been studied extensively owing not only to the biological importance of the metal−nucleobase bonds but also to their structural diversity and molecular recognition, which are applicable to developments of advanced functional materials.[1−4] Among the nucleobases, adenine and its derivatives (e.g., 9-alkyladenine and adenosine) give the most versatile coordination compounds, because they have three kinetically favored endocyclic sites, N(1), N(3), and N(7), to bind a metal ion (Chart 1).[5] Many transition-metal complexes containing monodentate N(7)- or N(1)-bound adenine,[1,2,4b,5,6] as well as a fewer number of those with N(3)-bound,[7a] N(9)-bound,[3,8,9a] N(6)-bound,[9b] and C(8)-bound[10] adenine (or its derivatives), have been prepared, and their protonation and

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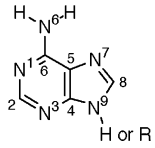
Chart 1



hydrogen-bonding properties have been investigated theoretically[11] and experimentally.[1,12−14] In contrast, for the N(9)-deprotonated adeninate (ade^-) only a limited number of complexes have been reported so far.[6c,7b,15,16] The coordination compounds bearing monodentate N(9)-bound adeninate may be somewhat related to the adenosine having (2-deoxy)-D-ribose at the N(9) site, and it should be interesting to compare the protonation and/or hydrogen-bonding abilities of such adeninate complexes to those of adenine or adenosine. For this purpose, we deal with the kinetically inert cobalt(III) complexes containing monodentate N(9)-bound adeninate (ade-κN^9). Although Kistenmacher et al. have reported a full crystal structure analysis of *cis*-[Co(ade-κN^9)-$Cl(en)_2$]$Br\cdot H_2O$,[15] they did not describe the detailed preparative procedure and the properties of this complex, and no other Co^{III} complexes of ade-κN^9 have been reported to date to our knowledge. In this study, we have established the syntheses of both geometrical (*cis* and *trans*) isomers of [Co-(ade-κN^9)$Cl(en)_2]^+$ ([**1**]$^+$), and examined their protonation behavior and hydrogen-bonding interactions.

Experimental Section

***cis*-[Co(ade)Cl(en)$_2$]Cl·CH$_3$OH (*cis*-[1]Cl·CH$_3$OH).** To a suspension of *trans*-$[CoCl_2(en)_2]Cl$[17] (4.6 g, 16 mmol) in methanol (50 cm^3) was added a methanol solution (50 cm^3) containing NaOH (0.65 g, 16 mmol) and adenine (2.2 g, 16 mmol). The mixture was stirred for 4 h at ambient temperature, and the resulting red precipitate was collected by filtration. The crude product was dissolved in a minimum amount of water, and methanol was added to the filtered solution, giving red crystals. Yield: 3.6 g (53%). Anal. Found: C, 28.69; H, 5.76; N, 30.60. Calcd for $C_{10}H_{24}Cl_2CoN_9O$: C, 28.86; H, 5.81; N, 30.29.

***cis*-[Co(ade)Cl(en)$_2$]BF$_4$ (*cis*-[1]BF$_4$).** This complex salt was prepared by a stoichiometric deprotonation from *cis*-[Co(Hade)-$Cl(en)_2](BF_4)_2$ (*cis*-[**2**]$(BF_4)_2$; vide infra). Sodium hydroxide (0.10 g, 2.6 mmol) was added to an aqueous solution of *cis*-[**2**]$(BF_4)_2\cdot 0.5H_2O\cdot 0.5CH_3OH$ (1.4 g, 2.6 mmol). The mixture was stirred for a while, and evaporated to dryness under reduced pressure. The residue was extracted with acetonitrile, and the crude product obtained by evaporation of the extract was recrystallized from methanol/diethyl ether, affording red microcrystals. Yield: 0.98 g (73%). Anal. Found: C, 24.78; H, 4.58; N, 28.54. Calcd for $C_9H_{20}BClCoF_4N_9$: C, 24.82; H, 4.63; N, 28.95.

***cis*-[CoCl(Hade)(en)$_2$]Cl$_2$·0.5H$_2$O (*cis*-[2]Cl$_2$·0.5H$_2$O).** The complex *cis*-[**1**]Cl·CH_3OH (1.0 g, 2.4 mmol) was dissolved in a minimum amount of water, and 1.2 N hydrochloric acid (2.0 cm^3) was added to the solution. The mixture was concentrated under reduced pressure to be nearly saturated, and ethanol was added to the concentrate to deposit red columnar crystals. Yield: 0.75 g (73%). Found: C, 25.12; H, 5.08; N, 29.31. Calcd for $C_9H_{22}Cl_3CoN_9O_{0.5}$: C, 25.16; H, 5.16; N, 29.34.

***cis*-[Co(H$_2$ade)Cl(en)$_2$]Cl$_3$·1.5H$_2$O (*cis*-[3]Cl$_3$·1.5H$_2$O).** The complex *cis*-[**1**]Cl·CH_3OH (65 mg, 0.16 mmol) was dissolved in a minimum amount of water, and 1.2 N hydrochloric acid (0.32 cm^3) was added. The mixture was concentrated under reduced pressure, and methanol was added to the concentrate to afford red columnar crystals. Yield: 57 mg (75%). Found: C, 22.18; H, 5.01; N, 26.03. Calcd for $C_9H_{25}Cl_4CoN_9O_{1.5}$: C, 22.33; H, 5.21; N, 26.04.

***cis*-[Co(H$_2$ade)Cl(en)$_2$]Cl$_2$(BF$_4$)·H$_2$O (*cis*-[3]Cl$_2$(BF$_4$)·H$_2$O).** To a solution of *cis*-[**2**]$Cl_2\cdot 0.5H_2O$ (0.52 g, 1.2 mmol) in a minimum amount of water were added 1.2 N hydrochloric acid (1.0 cm^3) and $NaBF_4$ (0.13 g, 1.2 mmol). The mixture was concentrated under reduced pressure, and the concentrate was diluted with the same volume of methanol. Addition of diethyl ether to this mixture gave a red precipitate, which was filtered off and recrystallized from aqueous ethanol to afford red columnar crystals. Yield: 0.25 g (40%). Found (the sample was partially effloresced): C, 21.19; H, 4.73; N, 24.43. Calcd for *cis*-[**3**]$(BF_4)Cl_2\cdot 0.5H_2O$ = $C_9H_{23}BCl_3CoF_4N_9O_{0.5}$: C, 20.89; H, 4.48; N, 24.43.

***trans*-[Co(ade)Cl(en)$_2$]BF$_4$·H$_2$O (*trans*-[1]BF$_4$·H$_2$O).** To a methanol solution (300 cm^3) of *cis*-[**2**]$(BF_4)_2\cdot 0.5H_2O\cdot 0.5CH_3OH$ (0.52 g, 0.94 mmol) was added a methanol solution of sodium methoxide (18%, 0.24 g, 1.4 mmol). The mixture was evaporated to dryness under reduced pressure, and the residue was dissolved in a minimum amount of hot water. The filtered solution was allowed to stand in a refrigerator overnight, affording red columnar crystals. Yield: 80 mg (19%). Anal. Found: C, 24.10; H, 5.01; N, 27.92. Calcd for $C_9H_{22}BClCoF_4N_9O$: C, 23.84; H, 4.89; N, 27.80.

***cis*-[CoCl(Hade)(en)$_2$](BF$_4$)$_2$·0.5H$_2$O·0.5CH$_3$OH (*cis*-[2](BF$_4$)$_2$·0.5H$_2$O·0.5CH$_3$OH) and *trans*-[CoCl(Hade)(en)$_2$](BF$_4$)$_2$·H$_2$O (*trans*-[2](BF$_4$)$_2$·H$_2$O).** An aqueous solution (100 cm^3) of *cis*-[**1**]-Cl·CH_3OH (3.4 g, 8.2 mmol) was poured onto a column of Sephadex QAE A-25 (BF_4^- form, 3 cm ∅ × 50 cm length), and a red band was eluted with water. The red solution collected was evaporated to dryness under reduced pressure, and the red residue was extracted with methanol. Diethyl ether was added to the extract to give a red powder of *cis*-[**2**]$(BF_4)_2\cdot 0.5H_2O\cdot 0.5CH_3OH$. Yield: 3.4 g (32%). Anal. Found: C, 20.35; H, 4.49; N, 23.05. Calcd for $C_{9.5}H_{24}B_2ClCoF_8N_9O$: C, 20.81; H, 4.41; N, 22.99. On extraction with methanol there remained a red insoluble material, which was then thoroughly washed with methanol. The red product was dissolved in a minimum amount of hot water, and the filtered solution was allowed to stand in a refrigerator overnight, depositing red columnar crystals of *trans*-[**2**]$(BF_4)_2\cdot H_2O$. Yield: 0.53 g (12%). Anal. Found: C, 20.00; H, 4.16; N, 23.24. Calcd for $C_9H_{23}B_2ClCoF_8N_9O$: C, 19.97; H, 4.28; N, 23.29.

***trans*-[Co(ade)(OH)(en)$_2$]BF$_4$·H$_2$O (*trans*-[4]BF$_4$·H$_2$O) and *cis*-[Co(ade)(OH)(en)$_2$]BF$_4$·1.5CH$_3$OH·NaCl (*cis*-[4]BF$_4$·1.5CH$_3$OH·NaCl).** Sodium hydroxide (0.10 g, 2.5 mmol) was dissolved in an aqueous solution (30 cm^3) containing *cis*-[**2**]$(BF_4)_2\cdot 0.5H_2O\cdot 0.5CH_3$-

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Table 1. Crystal Data for *cis*-[Co(ade)Cl(en)$_2$]Cl·CH$_3$OH, *cis*-[CoCl(Hade)(en)$_2$]Cl$_2$·0.5H$_2$O, *cis*-[Co(H$_2$ade)Cl(en)$_2$]Cl$_2$(BF$_4$)·H$_2$O, *trans*-[CoCl(Hade)(en)$_2$](BF$_4$)$_2$·H$_2$O, and *trans*-[Co(ade)(H$_2$O)(en)$_2$]HPO$_4$·3H$_2$O

	cis-[**1**]Cl·CH$_3$OH	*cis*-[**2**]Cl$_2$·0.5H$_2$O	*cis*-[**3**]Cl$_2$(BF$_4$)·H$_2$O	*trans*-[**2**](BF$_4$)$_2$·H$_2$O	*trans*-[**5**]HPO$_4$·3H$_2$O
emprical formula	$C_{10}H_{24}Cl_2CoN_9O$	$C_9H_{22}Cl_3CoN_9O_{0.5}$	$C_9H_{24}BCl_3CoF_4N_9O$	$C_9H_{23}B_2ClCoF_8N_9O$	$C_9H_{29}CoN_9O_8P$
fw	416.21	429.64	526.46	541.36	481.31
cryst syst	monoclinic	triclinic	monoclinic	monoclinic	orthorhombic
a/Å	23.367(5)	10.4934(19)	9.432(2)	9.248(3)	13.887(2)
b/Å	7.852(2)	12.522(2)	14.584(2)	17.372(4)	15.501(3)
c/Å	19.576(4)	13.242(2)	15.556(2)	12.754(2)	9.288(3)
α/deg	90	90.847(15)	90	90	90
β/deg	102.751(15)	95.685(15)	103.835(14)	91.004(18)	90
γ/deg	90	96.589(14)	90	90	90
U/Å^3	3503.0(13)	1719.3(5)	2077.7(7)	2048.7(8)	1999.3(8)
space group	*C*2/*c* (No. 15)	$P\bar{1}$ (No. 2)	*P*2$_1$/*c* (No. 14)	*P*2$_1$/*a* (No. 14)	*P*2$_1$2$_1$2$_1$ (No. 19)
Z	8	4	4	4	4
D_{calcd}/Mg m^{-3}	1.578	1.660	1.683	1.755	1.599
μ(Mo Kα)/mm^{-1}	1.303	1.478	1.268	1.062	0.996
R1[a](F^2)[b] (obsd)	0.051	0.041	0.058	0.046	0.048
wR2[c](F^2) (all)	0.149	0.133	0.204	0.144	0.139

[a] $R1 = \sum||F_o| - |F_c||/\sum|F_o|$. [b] $F^2 > 2\sigma(F^2)$. [c] $wR2 = [\sum w(|F_o| - |F_c|)^2/\sum|F_o|^2]^{1/2}$.

OH (0.48 g, 0.88 mmol). The solution was evaporated to dryness under reduced pressure, and the residue was extracted with a minimum amount of hot water. The extract was stored in a refrigerator overnight, depositing orange columnar crystals of *trans*-[**4**]BF$_4$·H$_2$O, which were collected by filtration. Yield: 80 mg (21%). Anal. Found: C, 24.91; H, 5.61; N, 28.88. Calcd for $C_9H_{23}BCoF_4N_9O_2$: C, 24.85; H, 5.33; N, 28.97. The red filtrate was neutralized with 1.2 N hydrochloric acid to pH 8. This solution was evaporated, again, to dryness, and the residue was extracted with acetonitrile. Evaporation of the extract gave crude product, which was recrystallized from methanol to afford red microcrystals of *cis*-[**4**]BF$_4$·1.5CH$_3$OH·NaCl. Yield: 0.16 g (34%). Found: C, 24.37; H, 5.27; N, 23.98. Calcd for $C_{10.5}H_{27}BClCoF_4N_9NaO_{2.5}$: C, 24.09; H, 5.20; N, 24.08.

***trans*-[Co(ade)(H$_2$O)(en)$_2$]HPO$_4$·3H$_2$O (*trans*-[5]HPO$_4$·3H$_2$O).** To an aqueous solution (10 cm^3) of *trans*-[**4**]BF$_4$·H$_2$O (0.19 g, 0.43 mmol) was added NaH_2PO_4 (0.21 g, 1.3 mmol). The mixture was stirred at ambient temperature for 20 min, and the resulting orange precipitate was filtered off. The precipitate was dissolved in a minimum amount of water, and the filtered solution was evaporated slowly at ambient temperature, affording orange columnar crystals. Yield: 42 mg (20%). Anal. Found: C, 22.34; H, 5.97; N, 26.00. Calcd for $C_9H_{29}CoN_9O_8P$: C, 22.46; H, 6.07; N, 26.19.

Crystallography. The X-ray intensities were measured up to $2\theta = 60°$ at 23(2) °C with graphite-monochromated Mo Kα radiation ($\lambda = 0.71073$ Å) on a Rigaku four-circle diffractometer, AFC-5R or -7R. Absorption corrections were made either by the numerical integration method[18a] or by an empirical Ψ-scan method.[18b] The structures were solved by the direct method using the SHELXS97[19] or SIR-92[20] program and refined on F^2 with all independent reflections by the full-matrix least-squares method using the SHELXL97 program.[19] All non-H atoms were refined anisotropically. All H atoms of the complex cations could be located in the difference Fourier syntheses maps, but they are placed at the theoretically calculated positions and treated with riding models. All calculations were carried out on an SGI Indy workstation using teXsan software.[21] The crystallographic data are summarized in Table 1.

Measurement. The 1-D ^{1}H NMR spectra were acquired at 30 °C on a JEOL JMN-EX270 spectrometer, while the ^{1}H−^{1}H NOESY spectra were recorded at 30 °C on a Varian Unity-Inova 600 MHz spectrometer. UV−vis absorption spectra were measured on a Perkin-Elmer Lambda 19 spectrophotometer at room temperature (∼20 °C). ESI-mass spectra were obtained on a Perkin-Elmer API-III mass spectrometer. The pH titration experiments were carried out at 20 °C with a Horiba N-8F ion meter and a 6069-10C glass electrode. Aqueous solutions of *cis*-[**1**]Cl (0.4−0.7 mM, $I = 0.1$ M, NaCl or NaClO$_4$) and *trans*-[**1**]BF$_4$ (0.25−0.5 mM, $I = 0.1$ M, NaCl) were titrated with aqueous HCl (5−10 mM, $I = 0.1$ M, NaCl or NaClO$_4$). The pK_a values were determined by the nonlinear curve fitting procedure based on the standard method reported by Kankare.[22] The pD-dependent ^{1}H NMR experiments were performed with a D$_2$O solution of *cis*-[**1**]Cl (1.0 mM) or *trans*-[**1**]BF$_4$ (1.0 mM, 0.1 M NaCl) and DCl. The pD values of the samples were corrected by adding 0.40 to the observed pH-meter reading (pD = pH* + 0.40).[23]

Results and Discussion

***cis*-[Co(ade)Cl(en)$_2$]$^+$ and Its Protonated Complexes.** Although Kistenmacher et al. reported the crystal structure

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(22) During the titration the relation between the added volume of HCl solution, V_{cal}, and the concentration of H$^+$ can be expressed (Kankare, J. J. *Talanta* **1975**, *22*, 1005−1012.) as

$$V_{cal} = \left\{ \frac{\frac{[H^+]}{K_2} + 2\frac{[H^+]^2}{K_1K_2}}{1 + \frac{[H^+]}{K_2} + \frac{[H^+]^2}{K_1K_2}} C_B^{\,0} + \left([H^+] - \frac{K_W}{[H^+]}\right) \right\} \times \frac{V_B^{\,0}}{\left\{ C_A^{\,0} - \left([H^+] - \frac{K_W}{[H^+]}\right) \right\}} \quad (1)$$

where K_1 and K_2 are the first and the second dissociation constants of the doubly protonated complex, respectively, $C_A^{\,0}$ and $C_B^{\,0}$ are the concentrations of HCl and the complex, respectively, $V_B^{\,0}$ is the initial volume of the complex solution, and K_W is the ion product of water. The pK_a values of the complexes were determined by nonlinear curve fittings of eq 1 to the experimentally obtained pH titration curves. The fittings were carried out to minimize the sum of the residual squared, $S = S(V_{exptl} - V_{calcd})^2$, with the Microsoft Excel Solver program (Yoshimura, N.; Okazaki, M.; Nakagawa, N. *J. Chem. Software* **2001**, *7*, 191−196).

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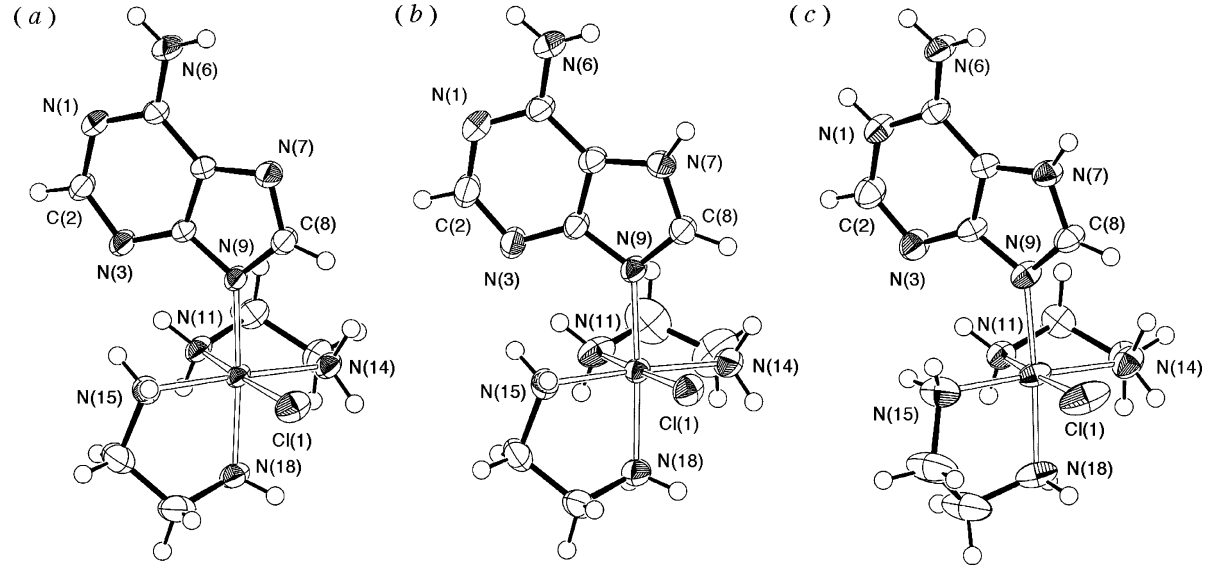

Figure 1. ORTEPs (50% probability levels) for the cationic parts of (a) *cis*-[**1**]Cl·CH_3OH, (b) *cis*-[**2**]Cl_2·0.5H_2O (one of the crystallographically independent cations), and (c) *cis*-[**3**]$Cl_2(BF_4)$·H_2O.

Table 2. Selected Bond Lengths (Å) and Angles (deg) of the Complexes

	cis-[**1**]Cl·CH_3OH	*cis*-[**2**]Cl_2·0.5H_2O[a]	*cis*-[**3**]$Cl_2(BF_4)$·H_2O	*trans*-[**2**]$(BF_4)_2$·H_2O	*trans*-[**5**]HPO_4·3H_2O
Co(1)−Cl(1)	2.2536(9)	2.242(1), 2.269(1)	2.267(1)	2.2309(8)	1.937(4)[b]
Co(1)−N(9)	1.950(2)	1.960(3), 1.950(3)	1.966(3)	1.961(2)	1.934(4)
Co(1)−N(11)	1.952(2)	1.957(3), 1.954(3)	1.950(3)	1.962(2)	1.964(4)
Co(1)−N(14)	1.956(2)	1.962(3), 1.958(3)	1.951(4)	1.965(2)	1.940(4)
Co(1)−N(15)	1.953(2)	1.963(3), 1.963(3)	1.961(4)	1.960(2)	1.967(4)
Co(1)−N(18)	1.967(2)	1.961(3), 1.958(3)	1.948(3)	1.972(2)	1.964(4)
N(1)−C(2)	1.342(4)	1.340(5), 1.335(5)	1.360(5)	1.344(4)	1.343(8)
N(1)−C(6)	1.340(4)	1.343(4), 1.343(5)	1.368(5)	1.348(4)	1.348(7)
N(3)−C(2)	1.328(3)	1.329(4), 1.328(5)	1.314(5)	1.326(3)	1.326(7)
N(3)−C(4)	1.351(3)	1.350(4), 1.346(4)	1.357(5)	1.336(3)	1.347(7)
N(7)−C(5)	1.393(3)	1.377(4), 1.382(4)	1.367(5)	1.371(3)	1.376(6)
N(7)−C(8)	1.333(3)	1.338(4), 1.334(4)	1.332(5)	1.333(3)	1.323(7)
N(9)−C(4)	1.376(2)	1.382(4), 1.386(4)	1.378(4)	1.387(3)	1.370(6)
N(9)−C(8)	1.362(3)	1.328(4), 1.334(4)	1.332(5)	1.333(3)	1.366(6)
C(2)−N(1)−C(6)	118.6(2)	119.3(3), 119.7(3)	124.2(3)	118.7(2)	118.5(5)
C(2)−N(3)−C(4)	112.2(2)	112.1(3), 111.5(3)	112.9(3)	112.2(2)	111.9(5)
C(5)−N(7)−C(8)	102.5(2)	106.8(3), 107.3(3)	106.7(3)	107.2(2)	103.2(4)
C(4)−N(9)−C(8)	103.3(2)	105.3(3), 105.2(2)	104.7(3)	104.9(2)	103.4(4)

[a] The second numbers in this column are the corresponding bond lengths and angles of the other crystallographically independent molecule with a Co(2) atom. [b] Co(1)−O(1).

of *cis*-[Co(ade)Cl(en)$_2$]Br·H_2O (*cis*-[**1**]Br·H_2O),[15] we have started our study by establishing a higher yield preparative method of *cis*-[**1**]$^+$, because the reported reaction of *trans*-[$CoCl_2$(en)$_2$]Cl with adenine in water did not afford the desired adeninato complex. We have found that a stoichiometric reaction of *trans*-[$CoCl_2$(en)$_2$]Cl, adenine, and NaOH in methanol, followed by recrystallization from aqueous methanol, gave red columnar crystals of *cis*-[**1**]Cl·CH_3OH in a moderate yield. The crystal structure of *cis*-[**1**]Cl·CH_3-OH was determined by X-ray analysis, which revealed the structure of the cationic complex having a monodentate N(9)-bound adeninate (ade-κN^9) in the position *cis* to Cl, as shown in Figure 1a. In the crystals of *cis*-[**1**]Cl·CH_3OH and *cis*-[**1**]Br·H_2O,[15] the intermolecular hydrogen-bonding scheme and the packing diagram are inherently different from each other owing to the different counteranions and solvated molecules of crystallization, while the molecular structures of *cis*-[**1**]$^+$ in these two crystals are apparently identical; there are no remarkable differences in their coordination bond lengths, bond angles, and structural parameters of the adeninate ligand (Table 2). Furthermore, the intramolecular hydrogen bonds were similarly located between adeninate N(3) and ethylenediamine N(11)−H/N(15)−H (Table 3), and the configuration around the Co atom and the conformations of the ethylenediamine chelate rings were also identical, $\Delta\lambda\lambda$/$\Lambda\delta\delta$.

The complex salt *cis*-[**1**]Cl·CH_3OH is well soluble in water, but insoluble in common organic solvents. In the ^{1}H NMR spectrum of *cis*-[**1**]Cl (1.0 mM) in D_2O,[24] the resonances due to C(2)−H and C(8)−H were observed at δ 8.16 and 8.18, respectively (these resonances were assigned

(24) There were no concentration dependences in the ^{1}H NMR chemical shifts of *cis*-[**1**]Cl (0.5−10 mM) and *trans*-[**1**]BF_4 (0.25−2 mM, 0.1 M NaCl) in D_2O, indicating that the complex cations were present in the monomeric forms without intermolecular hydrogen-bonding and/or stacking interactions in the range of concentration.

Table 3. Selected Intra- and Intermolecular Hydrogen-Bond Parameters of the Complexes

	D	A	D···A/Å	D−H/Å	H···A/Å	D−H···A/deg
cis-[**1**]Cl·CH_3OH	N(11)	N(3)	2.887(2)	0.900	2.116	143.16
	N(15)	N(3)	3.065(3)	0.900	2.322	139.78
	N(14)	N(7)[a]	3.068(3)	0.900	2.297	143.58
	N(15)	N(1)[b]	3.058(3)	0.900	2.277	144.96
cis-[**2**]Cl_2·0.5H_2O	N(11)	N(3)	3.016(4)	0.900	2.261	141.18
	N(15)	N(3)	2.953(4)	0.900	2.193	141.72
	N(211)	N(23)	2.995(4)	0.900	2.242	140.88
	N(215)	N(23)	2.931(4)	0.900	2.212	136.43
	N(7)	O(1)[c]	3.299(3)	0.860	3.040	99.92
	N(27)	O(1)	3.220(3)	0.860	2.963	99.58
	N(7)	Cl(21)[d]	3.127(2)	0.860	2.307	159.51
	N(27)	Cl(2)[e]	3.158(2)	0.860	2.352	156.21
cis-[**3**]$Cl_2(BF_4)$·H_2O	N(11)	N(3)	2.961(4)	0.900	2.198	142.15
	N(15)	N(3)	3.111(6)	0.900	2.634	114.03
	N(1)	Cl(2)[f]	3.117(3)	0.860	2.317	154.79
	N(7)	Cl(3)[g]	3.053(3)	0.860	2.262	152.84
trans-[**2**]$(BF_4)_2$·H_2O	N(11)	N(3)	2.920(3)	0.900	2.149	143.35
	N(15)	N(3)	3.025(3)	0.900	2.276	140.51
	N(7)	F(4)	3.281(5)	0.860	2.952	104.98
	N(7)	O(1)[h]	2.745(3)	0.860	1.936	156.24
	N(14)	N(1)[i]	3.115(3)	0.900	2.245	162.57
	N(18)	N(1)[i]	3.483(3)	0.900	2.715	143.88
trans-[**5**]HPO_4·3H_2O	N(14)	N(3)	2.839(6)	0.900	2.044	146.60
	N(18)	N(3)	3.217(6)	0.900	2.580	128.34
	O(14)	N(1)[j]	2.694(6)	0.820	1.889	166.86
	O(6)	N(7)[k]	2.803(6)	1.078	1.928	135.86
	N(6)	O(11)[l]	2.873(5)	0.860	2.026	168.42
	N(11)	O(14)[m]	3.043(6)	0.900	2.250	146.87
	N(14)	O(11)[n]	2.869(5)	0.900	1.982	168.26
	N(15)	O(12)	2.914(6)	0.900	2.052	160.02
	N(18)	O(8)	3.003(7)	0.900	2.197	148.75
	N(18)	O(13)[n]	3.061(7)	0.900	2.318	139.80
	O(1)	O(12)	2.570(5)	0.820	1.757	171.13
	O(1)	O(13)[n]	2.554(5)	0.820	1.737	174.10
	O(6)	O(11)	2.728(6)	1.034	1.710	166.92
	O(7)	O(13)[n]	2.897(7)	1.038	1.908	158.07
	O(7)	O(6)[o]	2.760(8)	0.971	1.842	156.62

[a] Symmetry operation: $-x + 1/2, -y + 1/2, -z + 1$. [b] Symmetry operation: $-x + 1/2, y - 1/2, -z + 1/2$. [c] Symmetry operation: $x, -y - 1, z$. [d] Symmetry operation: $x + 1, y - 1, z$. [e] Symmetry operation: $x, y + 1, z$. [f] Symmetry operation: $-x + 1, y - 1/2, -z + 1/2$. [g] Symmetry operation: $x, -y + 1/2, z + 1/2$. [h] Symmetry operation: $x - 1/2, -y - 1/2, z$. [i] Symmetry operation: $x + 1, y, z$. [j] Symmetry operation: $x - 1, y, z$. [k] Symmetry operation: $x - 1/2, -y + 3/2, z + 1$. [l] Symmetry operation: $x + 1, y, z$. [m] Symmetry operation: $-x + 1/2, -y + 1, z - 1/2$. [n] Symmetry operation: $-x + 1/2, -y + 1, z + 1/2$. [o] Symmetry operation: $x, y, z + 1$.

on the basis of the $^1H-^1H$ NOESY spectrum of *cis*-[**2**]$(BF_4)_2$ in CD_3CN, vide infra). When DCl (in D_2O) was added to this solution, both resonances of C(2)−H and C(8)−H showed a downfield shift (Figure 2a). At any concentration of the added DCl, each resonance of C(2)−H or C(8)−H was observed as a single peak, although the lower field resonance due to C(8)−H became somewhat broader when the pD of the solution was in the range of 7 > pD > 5. This fact indicates that in acidic aqueous solution the complex was stable toward geometrical isomerization or decomposition, while protonation equilibrium to the coordinated adeninate moiety was suggested. The pH-titration experiment for *cis*-[**1**]Cl (20 °C, $I = 0.1$ M NaCl) indicated that two protons can add to *cis*-[**1**]$^+$ (Figure 3). The pK_a values for the first and the second protonated products were determined as 6.03(1) and 2.53(12), respectively (6.00(1) and 2.40(5) in 0.1 M aqueous $NaClO_4$ at 20 °C), which are remarkably larger than the corresponding values for adenine (pK_a = 4.2 for N(1)−H and −0.4 for N(7)−H)[25] and 9-methyladenine (pK_a = 4.10 for N(1)−H and −0.64 for N(7)−H),[26] suggesting the higher basicity of the adeninate ligand in *cis*-[**1**]$^+$. Since the C(8)−H resonance showed a greater downfield shift and broader line width than the C(2)−H resonance at the first protonation step (7 > pD > 5, Figure 2a), it is presumed that the first proton added to *cis*-[**1**]$^+$ resides at N(7).

Isolation of the monoprotonated complex from a stoichiometric mixture of *cis*-[**1**]Cl and HCl in water yielded red columnar crystals, which were characterized by X-ray analysis as *cis*-[CoCl(Hade)$(en)_2$]Cl_2·0.5H_2O (*cis*-[**2**]Cl_2·0.5H_2O). The crystal is composed of two crystallographically independent complex cations, four Cl^- anions, and a water molecule. The molecular structures of the two cationic complexes are similar to each other, and one of them is shown in Figure 1b. The coordination geometry around the Co^{III} center (including the coordination bond lengths and bond angles), the intramolecular hydrogen-bonding scheme, and the conformation of the ethylenediamine chelate rings are also similar to those of *cis*-[**1**]Cl·CH_3OH. The H atom bound to the adenine moiety could be found in the difference

(25) (a) Benoit, R. L.; Fréchette, M. *Can. J. Chem.* **1984**, *62*, 995−1000. (b) Benoit, R. L.; Fréchette, M. *Can. J. Chem.* **1985**, *63*, 3053−3056.

(26) Kampf, G.; Kapinos, L. E.; Griesser, R.; Lippert, B.; Sigel, H. *J. Chem. Soc., Perkin Trans. 2* **2002**, 1320−1327.

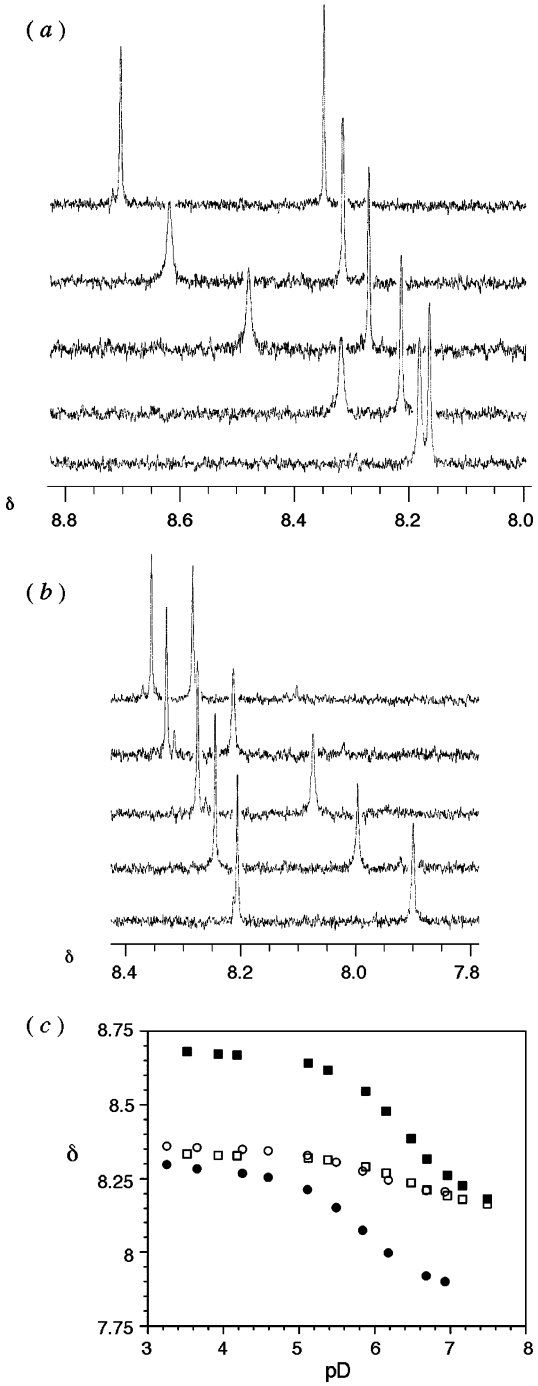

Figure 2. ^{1}H NMR spectra of (a) *cis*-[**1**]Cl (1.0 mM) in DCl/D_2O at pD 7.49, 6.69, 6.15, 5.38, and 3.07 (from bottom to top) and (b) *trans*-[**1**]BF_4 (1.0 mM) in DCl/NaCl (0.1 M)/D_2O at pD 6.93, 6.18, 5.88, 5.11, and 4.25 (from top to bottom). (c) Chemical shifts of C(2)−H (□) and C(8)−H (■) of *cis*-[**1**]Cl and C(2)−H (○) and C(8)−H (●) of *trans*-[**1**]BF_4 vs the pD of the solution.

Fourier synthesis map.[27] The position of the protonation was also confirmed by the endocyclic C−N−C bond angles and the intermolecular hydrogen-bonding interactions. It is known that the protonation at the cyclic N atom in the adenine enlarges the endocyclic C−N−C angle by 4−5°,[7] and the C(5)−N(7)−C(8) and C(25)−N(27)−C(28) angles of *cis*-[**2**]Cl_2·0.5H_2O are obviously larger by ∼5° than those of *cis*-[**1**]Cl·CH_3OH and *cis*-[**1**]Br·H_2O (Table 2). Furthermore, while N(7) in *cis*-[**1**]Cl·CH_3OH and *cis*-[**1**]Br·H_2O acts as a hydrogen-bond acceptor from the neighboring ethylenediamine N−H and from the water O−H, respectively, N(7)−H and N(27)−H in *cis*-[**2**]Cl_2·0.5H_2O are hydrogen-bond donors to the Cl^- anions. Therefore, the ligand in the monoprotonated complex *cis*-[**2**]$^{2+}$ is unambiguously characterized as 7*H*-Hade-κN^9 (an adenine tautomer), as inferred from ^{1}H NMR spectroscopy in solution (vide intra). This is in contrast to the manner of protonation of free adenine (or its N(9)-substituted derivatives), where it was proved theoretically,[11a] crystallographically (in the solid),[28] and spectroscopically (in solution)[25,26] that the first proton adds to the adenine residue at N(1). This fact suggests that the electronic nature of the N(9)-bound adeninate in the Co^{III} complex is somewhat different from those of adenine and adenosine, at least the order of basicities of their N(1) and N(7) atoms.

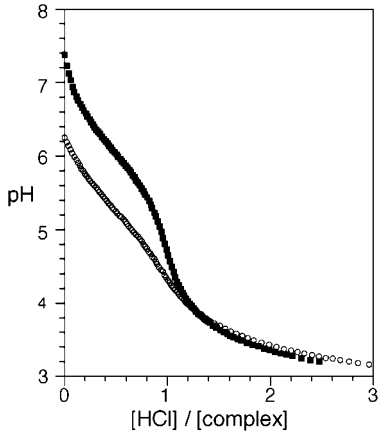

Figure 3. pH-titration (20 °C, I = 0.1 M NaCl) plots of *cis*-[**1**]Cl (■) and *trans*-[**1**]BF_4 (○) with HCl.

The complex salts of *cis*-[**1**]BF_4 and *cis*-[**2**]$(BF_4)_2$, which are soluble in acetonitrile, could also be isolated. The ^{1}H NMR spectra of *cis*-[**1**]BF_4 (5 mM) and *cis*-[**2**]$(BF_4)_2$ (11 mM) in CD_3CN showed seven broad resonances (one of them had twice the intensity of the others) due to the ethylenediamine N−H_2 in the range of δ 3.20−7.40, being consistent with their *cis* configuration. The adeninate/adenine tautomer N(6)−H_2 resonance was observed at δ 5.75 for *cis*-[**1**]BF_4 and at δ 6.48 for *cis*-[**2**]$(BF_4)_2$, and the C(2)−H and C(8)−H resonances were observed at values similar to those of *cis*-[**1**]Cl and *cis*-[**2**]Cl_2 in D_2O. In the ^{1}H−^{1}H NOESY spectrum of *cis*-[**2**]$(BF_4)_2$ in CD_3CN, a cross-peak was observed between the signals at δ 4.01 (one of the ethylenediamine N−H_2 resonances) and 8.61 (the lower field resonance in the aromatic region). As seen in Figure 1b, the molecular structure of *cis*-[**2**]$^{2+}$ suggests a stronger NOE for C(8)−H with ethylenediamine N−H_2 than for C(2)−H, and the signal at δ 8.61 can, therefore, be assigned as the C(8)−H resonance.

(27) Although these H atoms could be located in the difference Fourier syntheses maps, they were replaced at theoretically calculated positions in the final structural refinement cycles.

(28) (a) Kistenmacher, T. J.; Shigematsu, T. *Acta Crystallogr.* **1974**, *B30*, 166−168. (b) Shikata, K.; Ueki, T.; Mitsui, T. *Acta Crystallogr.* **1973**, *B29*, 31−38. (c) Hata, T.; Sato, S.; Kaneko, M.; Shimizu, B.; Tamura, C. *Bull. Chem. Soc. Jpn.* **1974**, *47*, 2758−2763.

From an equimolar mixture of *cis*-[**2**]Cl_2, HCl, and $NaBF_4$ in water, red columnar crystals were isolated by addition of methanol and diethyl ether. The X-ray crystallographic analysis revealed that the crystal consists of a cationic cobalt(III) complex that contains a doubly protonated adeninium ion (H_2ade^+-κN^9), two Cl^- anions, a BF_4^- anion, and a water molecule: *cis*-[$Co(H_2ade$-$\kappa N^9)Cl(en)_2$]$Cl_2(BF_4)\cdot H_2O$ (*cis*-[**3**]$Cl_2(BF_4)\cdot H_2O$). The bond angle C(2)−N(1)−C(6) became larger by ∼5° than those in *cis*-[**2**]$^{2+}$ (Table 2), being consistent with the second protonation at N(1).[27] Also, both N(1)−H and N(7)−H act as hydrogen-bond donors to the Cl^- anions (Table 3). The structure of the 1*H*,7*H*-H_2ade^+-κN^9 ligand is very similar to those of doubly protonated adeninium and 9-methyladeninium dications.[29] As seen in Figure 1c, the equatorial ethylenediamine chelate ring, N(11)−C(12)−C(13)−N(14), has the same conformation as that found in *cis*-[**1**]Cl·CH_3OH and *cis*-[**2**]$Cl_2\cdot 0.5H_2O$, while the other ethylenediamine chelate ring, N(15)−C(16)−C(17)−N(18), has the opposite conformation; the absolute configuration of *cis*-[**3**]$^{3+}$ is thus represented as $\Delta\lambda\delta/\Lambda\delta\lambda$. However, since the intramolecular hydrogen bonds between N(3) and N(11)−H/N(15)−H are still observed in *cis*-[**3**]$^{3+}$, such hydrogen bonds may contribute to the coordination stability of the adeninium cation 1*H*,7*H*-H_2ade^+-κN^9.

The ^{1}H NMR spectra of *cis*-[**2**]Cl_2 and *cis*-[**3**]Cl_3 in D_2O were identical to those of 1:1 and 1:2 mixtures of *cis*-[**1**]Cl and DCl, respectively. Furthermore, an equimolar mixture of *cis*-[**2**]Cl_2 and NaOD and a 1:2 mixture of *cis*-[**3**]Cl_3 and NaOD reproduced the ^{1}H NMR spectrum of *cis*-[**1**]Cl. The latter fact is in contrast to the case of the analogous imidazole (Him) and benzimidazole (Hbzim) complexes *cis*-[CoCl(Him or Hbzim)$(en)_2$]$^{2+}$, where base hydrolysis gave a mixture of the geometrical isomeric pair of the corresponding hydroxo complexes *cis*- and *trans*-[Co(OH)(Him or Hbzim)$(en)_2$]$^{2+}$.[30] When *cis*-[**1**]Cl was dissolved in a NaOD/D_2O solution, the ^{1}H NMR spectrum showed two sets of resonances for C(2)−H and C(8)−H in an integration ratio of ca. 5 (δ 7.98 and 8.18):1 (δ 7.91 and 8.20), which indicated the formation of both geometrical isomers of the hydroxo complex, *cis*- and *trans*-[Co(ade)(OH)$(en)_2$]$^+$ (*cis*- and *trans*-[**4**]$^+$). Attempts to isolate these two complexes from an aqueous reaction mixture of *cis*-[**2**]$(BF_4)_2$ and excess NaOH (see the Experimental Section) afforded red microcrystalline solids (*cis*-[**4**]$BF_4\cdot 1.5CH_3OH\cdot$NaCl) and orange columnar crystals (*trans*-[**4**]$BF_4\cdot H_2O$) in 34% and 21% isolated yields, respectively. The isolated complexes were fully characterized by elemental analysis and UV−vis, ^{1}H NMR, and ESI-mass spectroscopies.

***trans*-[Co(ade)Cl$(en)_2$]$^+$ and Its Protonated Complexes.** To date, not only for the adeninato complex of [Co(ade)Cl$(en)_2$]$^+$ but also for the analogous imidazole and benzimidazole complexes of [CoCl(Him and Hbzim)$(en)_2$]$^{2+}$, the *trans*-isomers have not been reported. However, as described above, base hydrolysis of the *cis*-chloro complex gave a mixture of the *cis*- and *trans*-hydroxo complexes. This result prompted us to prepare and isolate the *trans*-chloro−adeninato (*trans*-[**1**]$^+$) and the related adenine tautomer (*trans*-[**2**]$^{2+}$) complexes, because we thought that there were no steric and/or electronic reasons to preclude the formation of these isomers other than the lack of an appropriate synthetic method. Our fruitful approach for isolation of *trans*-[**1**]$BF_4\cdot H_2O$ (in 19% isolated yield) was a reaction of *cis*-[**2**]$(BF_4)_2$ and a small excess of sodium methoxide in methanol, followed by recrystallization from hot water.

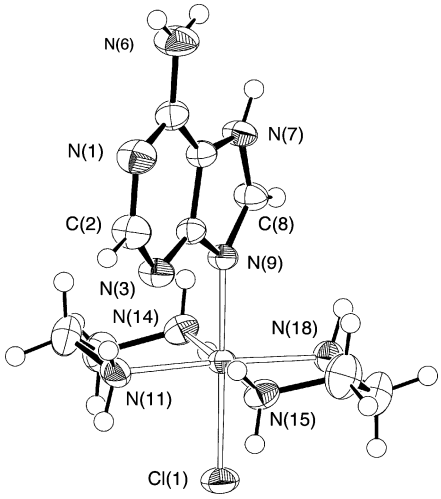

Figure 4. ORTEP (50% probability levels) for the cationic part of *trans*-[**2**]$(BF_4)_2\cdot H_2O$.

Similar to *cis*-[**1**]Cl, *trans*-[**1**]BF_4 showed base hydrolysis to give a mixture of *cis*- and *trans*-[**4**]$^+$ (in this case the formation ratio of the isomers was 1:1 as determined by ^{1}H NMR in NaOD/D_2O), while the complex in acidic solution was stable toward geometrical isomerization, but protonation to the coordinated adeninato ligand occurred. The pH titration of *trans*-[**1**]BF_4 (20 °C, I = 0.1 M NaCl) indicated two-step protonation (pK_a = 5.21(1) and 2.48(9)), similar to that of *cis*-[**1**]Cl (Figure 3). The ^{1}H NMR resonances due to C(2)−H and C(8)−H of *trans*-[**1**]BF_4 in D_2O (0.1 M NaCl)[24] were also downfield shifted on addition of DCl (Figure 2b). However, in contrast to the case of *cis*-[**1**]Cl, the higher field resonance in the aromatic region became broader in the pD range of 7 > pD > 4.5.

The *trans*-isomer of the monoprotonated complex *trans*-[**2**]$(BF_4)_2\cdot H_2O$ could be isolated as red columnar crystals, and the crystal structure was determined by X-ray analysis (Figure 4). The cationic complex in *trans*-[**2**]$(BF_4)_2\cdot H_2O$ has a pseudosymmetrical plane, and two equatorial ethylenediamine chelate rings have conformations opposite each other: $\delta\lambda$. Due to such conformations of ethylenediamine chelate rings, the intramolecular hydrogen bonds between adenine N(3) and ethylenediamine N(11)−H/N(15)−H would become most effective. The coordination bond lengths and bond angles around the Co atom and the intraligand structural parameters of the adenine moiety in *trans*-[**2**]$(BF_4)_2\cdot H_2O$ (Table 2) are almost identical to those in *cis*-[**2**]$Cl_2\cdot 0.5H_2O$;

(29) (a) Bryan, R. F.; Tomita, K.-I. *Acta Crystallogr.* **1962**, *15*, 1179−1182. (b) Langer, V.; Huml, K. *Acta Crystallogr.* **1978**, *B34*, 1157−1163.

(30) (a) Brodsky, N. R.; Nguyen, N. M.; Rowan, N. S.; Storm, C. B.; Butcher, R. J.; Sinn, E. *Inorg. Chem.* **1984**, *23*, 891−897. (b) Gomez-Vaamonde, M. C.; Nolan, K. B. *Inorg. Chim. Acta* **1985**, *101*, 67−70. (c) Coulter, G.; Krishnamurthy, M. *J. Inorg. Nucl. Chem.* **1977**, *39*, 1969−1970.

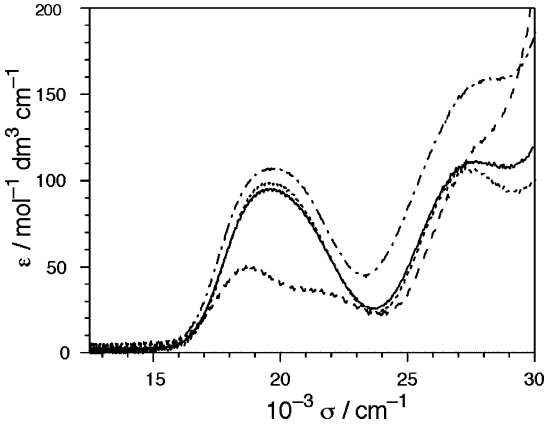

Figure 5. UV−vis absorption spectra of *cis*-[**1**]Cl in H_2O (-·--·-), *cis*-[**2**]Cl_2 in H_2O (—), *cis*-[**3**]Cl_3 in 0.01 M HCl(aq) (···), and *trans*-[**2**]$(BF_4)_2$ in CH_3CN (---) at ambient temperature.

the angle C(5)−N(7)−C(8) in *trans*-[**2**]$(BF_4)_2$·H_2O was also larger by ∼5° than the corresponding angles in *cis*-[**1**]$^+$ and free adenine (vide intra). Furthermore, in the crystal of *trans*-[**2**]$(BF_4)_2$·H_2O, N(7)−H[27] acts as a hydrogen-bond donor to the water molecule of hydration, while N(1) is an intermolecular hydrogen-bond acceptor from N(14)−H of the neighboring complex cation (Table 3). Thus, the protonation site to the coordinated adeninate in this *trans*-isomer is exclusively determined as N(7), i.e., 7*H*-Hade-κN.[9]

The ^{1}H NMR spectrum of *trans*-[**2**]$(BF_4)_2$ in CD_3CN (13 mM) gave two broad signals due to ethylenediamine N−H_2 at δ 4.69 and 5.26, and a broad signal at δ 6.66 for adenine N(6)−H_2. Two sharp resonances corresponding to C(2)−H and C(8)−H were observed at δ 8.35 and 8.23, and the higher field one showed a cross-peak with one of the ethylenediamine N−H_2 signals (δ 5.26) in the ^{1}H−^{1}H NOESY spectrum. Therefore, the signal at δ 8.23 can be assigned as the C(8)−H resonance. Because this higher field signal became broader in the pD range (7 > pD > 4.5) of the first protonation in contrast to that due to C(2)−H (Figure 2b), the first proton seems to add to N(7) of the adeninate ligand in *trans*-[**1**]$^+$, similar to the case of the corresponding *cis*-isomer *cis*-[**1**]$^+$.

For the *trans*-isomer, the doubly protonated complex *trans*-[**3**]$^{3+}$ could not be isolated. However, since it was suggested from the crystal structures of *cis*- and *trans*-[**2**]$^{2+}$ that there is no significant difference in the electronic properties of the coordinated adenine moiety between the geometrical isomers, the second proton is presumed to add to N(1) also for the *trans*-isomer.

UV−Vis Absorption Spectra of the Adeninate/Adenine Tautomer Complexes. The UV−vis absorption spectra of *cis*-[**1**]$^+$, *cis*-[**2**]$^{2+}$, *cis*-[**3**]$^{3+}$, and *trans*-[**2**]$^{2+}$ are shown in Figure 5. It is clear that the protonation to the coordinated adeninate moiety did not alter the spectra significantly, especially in the region of 15000−30000 cm^{-1}. Thus, the ligand-field strengths of adeninate-κN^9, 7*H*-adenine-κN^9, and 1*H*,7*H*-adeninium-κN^9 are almost identical to one another, irrespective of the anionic, neutral, and cationic forms. The *cis*-isomers showed two broad absorption bands assignable to the first and the second d−d transitions around 19500 and 27500 cm^{-1}, respectively. The first d−d bands of these complexes are located at slightly higher energy than that of *cis*-[CoCl(Him)$(en)_2$]$^{2+}$ (19050 cm^{-1}),[30c] suggesting that the ligand-field strengths of ade$^-$, Hade, H_2ade$^+$-κN^9 are a little higher than that of Him. For *trans*-[**2**]$^{2+}$, explicit splitting of the first d−d band was observed; the Gaussian curve fitting analysis gave two bands at 18390 cm^{-1} (a^1E_g, ϵ = 31.0 mol^{-1} dm^3 cm^{-1}) and 21110 cm^{-1} ($^1A_{2g}$, ϵ = 31.1 mol^{-1} dm^3 cm^{-1}) in addition to a second d−d band at 27100 cm^{-1} (ϵ = 67.2 mol^{-1} dm^3 cm^{-1}). With these transition energies observed, the empirical ligand parameter[31] of the adenine tautomer was calculated as d(Hade) = 19500 cm^{-1}; the parameter of Him has been reported as d(Him) = 21200 cm^{-1},[31] but the present study suggests that the value for Him should be a little smaller than d(Hade) = 19500 cm^{-1}.

Hydrogen-Bonding Interaction of *cis*- and *trans*-[Co(ade or Hade)Cl$(en)_2$]$^{n+}$ and a Uracil Derivative in Solution. To investigate the hydrogen-bonding interactions between the adeninate/adenine tautomer complexes and a uracil derivative in solution, the concentration-dependent ^{1}H NMR spectra[5,12b] of an equimolar mixture of 1-cyclohexyluracil (1-CyU) and *cis*-[**1**]BF_4, *cis*-[**2**]$(BF_4)_2$, or *trans*-[**2**]$(BF_4)_2$ in acetonitrile-d_3 have been acquired (Table 4). It has been established that 1-CyU and 9-ethyladenine form Watson−Crick-type hydrogen bonds in solution,[32] where both the uracil N(3)−H and adenine N(6)−H_2 resonances gave a downfield shift as compared to those of the individual samples.

The ^{1}H NMR spectra of 1-CyU in CD_3CN at a concentration of 1.1−9.6 mM did not show a significant concentration dependence; a broad signal due to N(3)−H gave a slight downfield shift from δ 8.76 (1.1 mM) to δ 8.92 (9.6 mM) at higher concentration (other signals were not shifted with increasing concentration, Table 4). The equimolar (2.5 mM) mixture of 1-CyU and *cis*-[**1**]BF_4 displayed a uracil N(3)−H resonance at δ 9.11 and an adeninate N(6)−H_2 resonance at δ 5.79, both of which were downfield shifted compared to those of the individual samples (with a similar concentration). Further, such resonances of the mixture showed obvious concentration dependences: downfield shifts with increasing concentration. In the spectrum of the 4.4 mM mixture, the uracil N(3)−H resonance was observed as a very broad signal centered at $\delta \approx 9.4$ ($\Delta_{1/2}$ = 70 Hz). These results suggest that a hydrogen-bonding interaction exists between 1-CyU and *cis*-[**1**]BF_4 in acetonitrile. However, neither the C(2)−H and C(8)−H resonances of *cis*-[**1**]$^+$ nor the C(5)−H and C(6)−H resonances of 1-CyU gave a significant change in their chemical shift on pairing (and a change in concentration).

In the case of an equimolar mixture of 1-CyU and *cis*-[**2**]$(BF_4)_2$, concentration-dependent chemical shift changes of the uracil N(3)−H and the adenine N(6)−H_2 resonances and broadening of the N(3)−H signal at higher concentration (e.g., at 8.4 mM, the signal for N(3)−H is at $\delta \approx 9.0$, $\Delta_{1/2}$ = 87 Hz) were similarly observed, although the chemical

(31) Shimura, Y. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 693−698.
(32) Nagel, G. M.; Hanlon, S. *Biochemistry* **1972**, *11*, 816−830.

Table 4. ^{1}H NMR Chemical Shifts of 1-CyU and a 1:1 Mixture of 1-CyU and *cis*-[**1**]BF_4, *cis*-[**2**]$(BF_4)_2$, or *trans*-[**2**]$(BF_4)_2$ in CD_3CN at 303 K

		uracil			adeninato/adenine tautomer		
compound	concn/mM	N(3)−H ($\Delta_{1/2}$/Hz)	C(5)−H	C(6)−H	C(8)−H	C(2)−H	N(6)−H
1-CyU	9.6	8.82 (34)	7.39	5.54			
	4.8	8.79 (35)	7.39	5.54			
	2.6	8.77 (33)	7.39	5.54			
	1.1	8.76 (35)	7.39	5.54			
cis-[**1**]BF_4	5.0				8.08	7.96	5.75
1-CyU + *cis*-[**1**]BF_4	4.4	~9.4 (70)	7.40	5.54	8.09	7.99	5.84
	2.5	9.11 (52)	7.40	5.55	8.09	7.97	5.79
	1.3	8.97 (49)	7.40	5.54	8.09	7.97	5.75
	0.94	8.95 (45)	7.40	5.54	8.09	7.97	5.74
	0.63	8.90 (37)	7.39	5.54	8.09	7.97	5.72
cis-[**2**]$(BF_4)_2$	11				8.61	8.33	6.48
1-CyU + *cis*-[**2**]$(BF_4)_2$	9.6	~9.0 (87)	7.40	5.55	8.61	8.33	6.51
	4.8	~8.9 (63)	7.40	5.55	8.60	8.33	6.49
	2.4	8.83 (49)	7.39	5.54	8.60	8.33	6.47
	1.2	8.79 (42)	7.39	5.54	8.59	8.33	6.46
	0.60	8.78 (38)	7.39	5.54	8.58	8.33	6.45
trans-[**2**]$(BF_4)_2$	13				8.23	8.35	6.66
1-CyU + *trans*-[**2**]$(BF_4)_2$	9.4	8.95 (35)	7.41	5.55	8.22	8.35	6.71
	4.7	8.86 (32)	7.40	5.55	8.20	8.34	6.68
	2.7	8.83 (32)	7.40	5.54	8.18	8.34	6.67
	1.3	8.80 (30)	7.39	5.54	8.17	8.33	6.64
	0.67	8.75 (27)	7.39	5.54	8.12	8.32	6.63

shift changes of this mixture were smaller than those of the mixture of 1-CyU and *cis*-[**1**]BF_4. The complex *cis*-[**2**]$^{2+}$ is presumably protonated at N(7), but the same type of hydrogen-bonding interaction with 1-CyU as for *cis*-[**1**]$^+$ is suggested. This fact may lead to the conclusion of the formation of the Watson−Crick-type pairing between 1-CyU and adeninate in *cis*-[**1**]$^+$ or adenine tautomer in *cis*-[**2**]$^{2+}$. The smaller downfield shifts for *cis*-[**2**]$^{2+}$ upon interaction with 1-CyU than those for *cis*-[**1**]$^+$ would result from a weaker basicity of the N(1) site of the protonated 7*H*-Hade than that of the unprotonated ade$^-$.[26]

In contrast to the above *cis*-isomers, the equimolar mixture of 1-CyU and *trans*-[**2**]$(BF_4)_2$ did not show a significant downfield shift nor a broadening of the uracil N(3)−H resonance (Table 4). The hydrogen-bonding interaction between 1-CyU and *trans*-[**2**]$^{2+}$ in acetonitrile seems to be very weak, although we cannot interpret the difference in hydrogen-bonding ability between *cis*- and *trans*-[**2**]$^{2+}$ at present. For a complete understanding of the hydrogen-bonding interaction of the adeninate/adenine tautomer in *cis*- and *trans*-[**1**]$^+$ and -[**2**]$^{2+}$, detailed experiments along this line are in progress.

Attempt To Prepare a Mixed-Ligand Adeninate and Phosphate Complex: Reactions of an Adeninato−Hydroxo Complex with Phosphate Ions. One of our future goals of this study is the synthesis of mixed-ligand nucleobase and phosphate complexes, which are nucleotide-mimic compounds having a transition-metal complex instead of (2-deoxy)-D-ribose. To this end, we have attempted to react [Co(ade)(OH)$(en)_2]^+$ ([**4**]$^+$) with phosphate salts. The ESI-mass spectrum of a mixture of *trans*-[**4**]BF_4 and Na_3PO_4 in aqueous (50%) methanol gave an envelope at $m/z = 721$, whose isotopic distribution corresponds to the composition of $C_{18}H_{40}Co_2O_4N_{18}P^+$. This may indicate the formation of a phosphate-bridged dinuclear complex, [(ade)$(en)_2$Co(μ-PO_4)-Co(ade)$(en)_2]^+$. A mixture of *cis*-[**4**]BF_4 and Na_3PO_4 showed a similar ESI-mass spectrum, but no compound could be isolated in a pure form from these solutions.

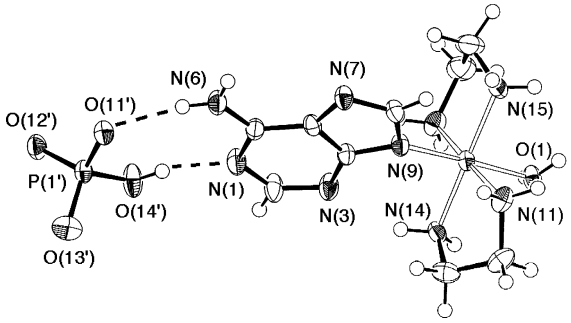

Figure 6. ORTEP (50% probability levels) for the cationic complex and the anion in *trans*-[**5**]$HPO_4 \cdot 3H_2O$, showing two hydrogen bonds between the adeninate ligand and hydrogen phosphate. Symmetry code for atom numbers followed by a prime: $x + 1, y, z$.

A reaction of *trans*-[**4**]BF_4 and excess NaH_2PO_4 in water, on the other hand, afforded orange columnar crystals. X-ray analysis revealed that the crystal is composed of an adeninato−aquo complex cation, hydrogen phosphate(2-) anion, and three water molecules: *trans*-[Co(ade)$(H_2O)(en)_2]HPO_4 \cdot 3H_2O$ (*trans*-[**5**]$HPO_4 \cdot 3H_2O$) (Figure 6). Neutralization of the hydroxo to aquo ligand occurred as expected, but a substitution reaction of phosphate ion for the aquo ligand could not proceed. Nevertheless, the crystal structure of *trans*-[**5**]$HPO_4 \cdot 3H_2O$ showed interesting intra- and intermolecular hydrogen-bond networks (Table 3). The HPO_4^{2-} anion was surrounded by four neighboring complex cations with hydrogen bonds, and one of these interactions was Watson−Crick-like hydrogen bonds with the coordinated adeninate (Figure 6). The adeninate N(7) is also acting as a hydrogen-bond acceptor from the water of crystallization. Although the intramolecular hydrogen bonds between adeninate N(3) and ethylenediamine $N-H_2$ were observed similarly to in *trans*-[**2**]$(BF_4)_2 \cdot H_2O$, the conformations of the ethylenediamine chelate rings were found as $\delta\delta$ (the crystal

was spontaneously resolved, space group $P2_12_12_1$). This conformational difference is due probably to the hydrogen-bonding interaction between HPO_4^{2-} and ethylenediamine N−H_2 protons.

Conclusion

In this study we have prepared a geometrical isomeric pair of cobalt(III) complexes containing monodentate N(9)-bound adeninate, *cis*- and *trans*-[Co(ade)Cl$(en)_2]^+$ ([**1**]$^+$). The *trans*-isomer was prepared and isolated for the first time. While base hydrolysis of both isomers gave a mixture of *cis*- and *trans*-[Co(ade)(OH)$(en)_2]^+$ ([**4**]$^+$), in acidic solution they were stable toward isomerization; at least two protons could add to the adeninate moiety in *cis*- and *trans*-[**1**]$^+$ without decomposition or geometrical isomerization of the Co^{III} coordination sphere. Since the pK_a values for the protonated complexes were determined as 6.03(1) and 2.53(12) for the *cis*-isomer, and 5.21(1) and 2.48(9) for the *trans*-isomer, it was shown that the adeninate complexes *cis*- and *trans*-[**1**]$^+$ have stronger basicity than (9-alkyl)adenine or adenosine.[26] In addition to the pD-dependent ^{1}H NMR spectral behavior of *cis*- and *trans*-[**1**]$^+$ in DCl/D_2O, the X-ray analyses of both isomers of the monoprotonated adenine tautomer complexes *cis*- and *trans*-[CoCl(Hade)$(en)_2]^{2+}$ ([**2**]$^{2+}$) revealed that the first proton resided on adeninate N(7). This is in contrast to the protonation of the free (9-alkyl)adenine or adenosine, where the first proton was bound to N(1).[11,25,26,28]

In the crystal structure of *trans*-[Co(ade)(H_2O)$(en)_2$]HPO_4·$3H_2O$, Watson−Crick-like hydrogen bonds were observed between the coordinated adeninate and HPO_4^{2-}. Furthermore, it was inferred from ^{1}H NMR spectroscopy that a mixture of *cis*-[**1**]$^+$/*cis*-[**2**]$^{2+}$ and 1-CyU in acetonitrile exhibited a hydrogen-bonding interaction. In conclusion, this study showed that cobalt(III) complexes of monodentate N(9)-bound adeninate have a potential to act as adenine derivatives with a higher protonation ability than adenine or adenosine.

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Supporting Information Available: X-ray crystallographic files, in CIF format, for *cis*-[**1**]Cl·CH_3OH, *cis*-[**2**]Cl_2·$0.5H_2O$, *cis*-[**3**]$Cl_2(BF_4)$·H_2O, *trans*-[**2**]$(BF_4)_2$·H_2O, and *trans*-[**5**]HPO_4·$3H_2O$. This material is available free of charge via the Internet at http://pubs.acs.org.

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