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# Synthesis and Characterization of Cobalt(III) Complexes Containing an *N*-Glycoside Derived from Ethylenediamine and an Aldose. Conformational Analysis of the Sugar Units by Means of Semiempirical AM1 Calculations

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**Abstract:** Substitution-inert cobalt(III) complexes containing an *N*-glycoside formed from ethylenediamine (en) and an aldose (D-mannose, L-rhamnose, or D-ribose) were synthesized by the oxidation of cobalt(II) to cobalt(III) in the presence of the diamine. It was found that $[(\mathrm{en})_2\mathrm{Co}(\mathrm{O}_2)(\mathrm{OH})\mathrm{Co}(\mathrm{en})_2]^{3+}$ is a reactive species toward aldoses in the reaction. The major product for each starting aldose was purified by column chromatography to yield red crystals. The isolated complexes were characterized by elemental analysis, conductivity measurements, and $^1$H and $^{13}$C NMR, electronic absorption, and circular dichroism spectroscopies, the results of which show that the complexes are composed of a bidentate en and a tetradentate *N*-glycoside ligand. The structures of the sugar units were analyzed by means of the semiempirical AM1 calculations coupled with the conversion of the vicinal $^1$H–$^1$H spin–spin coupling constants in the $^1$H NMR spectra into torsion angles of the corresponding H–C–C–H fragments. The results of the calculations demonstrate that the D-mannose and L-rhamnose units take the pyranose form with the $\beta$-$^3S_5$ skew-boat conformation on the cobalt(III) complexes, while the D-ribose unit adopts the furanose form with the $\alpha$-$^2E$ envelope conformation on the complex; in addition the sugar units of the *N*-glycoside ligands facially bind to the cobalt atom at three points through the donor atoms on C1, C2, and C3.

The interaction of sugars with various metal ions is well-known and is of current interest in bioinorganic chemistry in connection with metal-containing enzymes and industrial applications. Despite such a wide interest, very little is systematically known about the structural details of sugar–metal complexes.[2-6]

In order to elucidate the interaction between sugars and transition metals, we have extensively studied the synthesis and characterization of substitution-labile nickel(II) complexes containing *N*-glycoside(s) derived from the reaction of sugars and diamines.[7-11] During a series of our investigations about *N*-glycoside systems formed from an aldose and a diamine with primary amino groups such as ethylenediamine or trimethylenediamine,[7-9] the structures of $[\mathrm{Ni}(\mathrm{D\text{-}GlcN\text{-}en}$[12]$)_2]\mathrm{Br}_2\cdot4\mathrm{H}_2\mathrm{O}$[8] and $[\mathrm{Ni}(\mathrm{L\text{-}Rha\text{-}tn}$[13]$)_2]\mathrm{Br}_2\cdot2\mathrm{H}_2\mathrm{O}\cdot\mathrm{CH}_3\mathrm{OH}$[9] were determined by X-ray crystallography. The crystal structures clarified that the sugar units take the usual chair conformation and attach to the nickel atom at two points through the donor atoms on C1 and C2.

Generally, transition-metal complexes are divided, on the basis of their chemical properties, into two classes: substitution-labile and substitution-inert. Therefore, we have explored the isolation of substitution-inert complexes containing *N*-glycoside(s) with the hope of gaining an understanding of the coordination behavior of *N*-glycosides. Recently, we successfully synthesized typically substitution-inert cobalt(III) complexes containing an *N*-glycoside formed from ethylenediamine and an aldose (D-mannose, L-rhamnose, or D-ribose).[14] In order to clarify the stereochemistry of these complexes, we have designed a novel method suitable for the conformational analysis of the sugar units in the sugar–metal complex systems which is based on the semiempirical MO calculation together with the quantitative conversion of the vicinal $^1$H–$^1$H spin–spin coupling constants in the $^1$H NMR spectra into the torsion angles of the corresponding H–C–C–H fragments. We have quantitatively analyzed the structures of the sugar units by the application of the above method and discussed the coordination structures of the Co(III)–*N*-glycoside complexes.

In this paper, we report the details of the successful isolation and characterization of novel cobalt(III) complexes containing an *N*-glycoside derived from ethylenediamine and an aldose, including the conformational analysis of the sugar units by means of semiempirical MO calculations.

## Experimental Section

**Measurements.** Electronic absorption (AB) spectra were obtained on a Hitachi Model 340 recording spectrophotometer. Circular dichroism (CD) spectra were recorded on a Jasco J-500A spectropolarimeter. These measurements were made on aqueous solutions at concentrations near $2 \times 10^{-3}$ M. Molar conductivities were determined at $298 \pm 1$ K by using a DKK AOC-10 electronic chemical instrument. Conductivity measurements were made on aqueous solutions at concentrations near $1 \times 10^{-3}$ M. FT $^1$H and $^{13}$C NMR spectra were obtained at 399.65 and 100.40 MHz, respectively, on a JEOL GX-400 spectrometer. Sodium

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3-(trimethylsilyl)propionate-$d_4$ (TSP-$d_4$, $\delta = 0$ ppm) and 2-methyl-2-propanol ($\delta = 31.9$ ppm) were used as internal references for $^1$H and $^{13}$C NMR chemical shifts, respectively. $^{13}$C NMR spectra were measured under both low-power broad-band proton-decoupled and homo-gated proton-decoupled conditions.

**Materials.** All materials were of reagent grade and were used without further purification. $[(en)_2Co(O_2)(OH)Co(en)_2](ClO_4)_3{\cdot}H_2O$ was prepared by the method of Foong.[15] The following abbreviations are used: en, ethylenediamine; D-Man, D-mannose; L-Rha, L-rhamnose, 6-deoxy-L-mannose; D-Rib, D-ribose; D-Man-en, 1-[(2-aminoethyl)amino]-1-deoxy-D-Mannose; L-Rha-en, 1-[(2-aminoethyl)amino]-1,6-dideoxy-L-mannose; D-Rib-en, 1-[(2-aminoethyl)amino]-1-deoxy-D-ribose.

**Preparations. Method 1. Common Procedure.** A 0.60-g (10-mmol) sample of en and 10-mmol quantity of an aldose (D-mannose, 1.80 g, L-rhamnose monohydrate, 1.82 g, or D-ribose, 1.50 g) were dissolved in 250 mL of methanol, and the solution was refluxed with stirring. To the solution was added a methanol solution (100 mL) of $CoCl_2{\cdot}6H_2O$ (1.19 g, 5 mmol) in ca. 5-mL portions. As soon as each aliquot was added, the solution became brown and gradually turned wine red, indicating oxidation to cobalt(III). The addition of the total amount took ca. 40 min. The refluxing was continued for another 20 min. After being cooled, the solution was evaporated to dryness at room temperature. The residue was dissolved in water, and the solution was poured onto a column of SP-Sephadex C-25 cation-exchange resin in the sodium form (o.d. = 4.5 cm, $h = 70$ cm). A small amount of yellow organic fraction was removed by washing with 2 L of water. Elution with 0.01 M NaCl produced a broad red band as the major product and a large amount of brownish species which strongly adsorbed to the resin. The major product obtained from five batches of the reaction was collected. With any aldose, the $^1$H NMR spectrum indicated that the red band was a mixture of some sugar complexes. Then, after being desalted by Sephadex G-15 gel permeation chromatography, the mixture was resorbed on a column of Dowex 50W-X8 cation-exchange resin in the sodium form (o.d. = 4.5 cm, $h = 70$ cm). The chromatographic behavior and the procedure for the isolation of each cobalt(III)-*N*-glycoside complex was different according to the starting aldose as follows.

**Isolation of $\Delta$-[Co(D-Man-en)(en)]$ClO_4{\cdot}NaClO_4{\cdot}1.5H_2O$ (1).** Elution with 0.1 M $NaClO_4$ yielded two close red bands. The first band was in trace amounts and had a positive CD sign at 17 500 cm$^{-1}$, while the second band was major and had a negative CD peak at the same wavenumber. Then, the major eluant showing the negative CD sign was collected and desalted by gel permeation chromatography. The solution was evaporated to dryness below 35 °C to dryness. The residue was dissolved in a minimum amount of warm 1:2 water–ethanol mixture. The solution was left at room temperature to give red needlelike crystals: yield, 135 mg (0.9%). Anal. Calcd for $C_{10}H_{27}N_4O_{14.5}NaCl_2Co$: C, 20.42; H, 4.63; N, 9.53; Na, 3.91; Cl, 12.06. Found: C, 20.11; H, 4.21; N, 9.38; Na, 3.32; Cl, 12.07.

**Isolation of $\Lambda$-[Co(L-Rha-en)(en)]$Br{\cdot}H_2O$ (2).** Elution with 0.1 M $NaClO_4$ yielded two well-separated red bands; the first was major, while the second was in a trace amount. The major fraction was collected and desalted by gel permeation chromatography. The crystals of the perchlorate salt obtained from this solution were so hygroscopic that the counteranion was exchanged for $Br^-$ through a column of Dowex 1 anion-exchange ($Br^-$ form) resin. The eluant was evaporated below 35 °C followed by addition of excess ethanol to yield red crystalline solids. This crystalline product was recrystallized from a minimum amount of warm ethanol: yield, 220 mg (2.1%). Anal. Calcd for $C_{10}H_{26}N_4O_5BrCo$: C, 28.52; H, 6.22; N, 13.30; Br, 18.97. Found: C, 28.86; H, 6.23; N, 13.01; Br, 19.67.

**Isolation of $\Lambda$-[Co(D-Rib-en)(en)]$ClO_4{\cdot}2H_2O$ (3).** By elution with 0.1 M $NaClO_4$, the mixture was clearly separated into two red bands. The first was major, while the second was in trace amounts. The major fraction was collected and desalted by gel permeation chromatography. The eluant was evaporated below 35 °C followed by addition of excess ethanol to give red crystalline solid. This crude product was recrystallized from warm ethanol: yield, 230 mg (1.9%). Anal. Calcd for $C_9H_{26}N_4O_{10}ClCo$: C, 24.31; H, 5.89; N, 12.60; Cl, 7.97. Found: C, 24.12; H, 5.54; N, 12.47; Cl, 8.06.

**Method 2.** To a methanol solution (500 mL) of a 2-mmol sample of an aldose (D-Man, 0.36 g, L-Rha·$H_2O$, 0.36 g, or D-rib, 0.30 g) was added a 0.36-g (0.5-mmol) quantity of $[(en)_2Co(O_2)(OH)Co(en)_2](ClO_4)_3{\cdot}H_2O$ which did not completely dissolve in the solvent. The mixture was heated to reflux and, after ~1 h, yielded a homogeneous wine red solution. The resulting solution was treated according to the procedure described in method 1. For each starting aldose, the same complex that was isolated by method 1 was obtained as the major product, which was confirmed by AB, CD, and NMR spectroscopies.

**Conformational Analysis of Sugar Units on Cobalt(III)-*N*-Glycoside Complexes.** The vicinal proton–proton coupling constants ($^3J_{\mathrm{Ha,Hb}}$) were converted into the $H_a$–$C_a$–$C_b$–$H_b$ torsion angles ($\phi$, $-180 < \phi \leq 180°$) on the basis of the empirical equation proposed by Haasnoot et al. as shown in eq 1.[16]

$$^3J_{\mathrm{Ha,Hb}} = 13.70 \cos^2 \phi - 0.73 \cos \phi + \sum \Delta X_i \{0.56 - 2.47 \cos^2 (\xi_i \phi + 16.9|\Delta X_i|)\} \quad (1)$$

where $\Delta X_i$ is the correction parameter for the electronegativity of the substituent,[16–18] and $\xi_i$ is the correction parameter for the orientation of the substituent relative to the coupled protons.[16] The summation is over all the substituents attached to the $C_a$ and $C_b$ atoms. $\Delta X_i$ is defined as eq 2 by using the correction parameters for the electronegativity of the $\alpha$- and $\beta$-substituents ($\Delta X^\alpha$, $\Delta X^\beta$).[16]

$$\Delta X_i = \Delta X^\alpha - 0.14 \sum \Delta X^\beta{}_i \quad (2)$$

where the summation is over all the substituents attached to the $\alpha$-substituent. 1-Amino-1-deoxy-$\beta$-D-mannopyranose (*N*-D-Man), 1-amino-1,6-dideoxy-$\beta$-L-mannopyranose (*N*-L-Rha), and 1-amino-1-deoxy-$\alpha$-D-ribufuranose (*N*-D-Rib) were treated as the sugar units of the complexes **1**–**3**, respectively,[19] and the torsion angles were calculated for the H–C–C–H fragments on the sugar rings. A reasonable set of torsion angles was chosen for each sugar ring structure. The atomic coordinates of the sugar units were optimized by semiempirical AM1 calculations,[20] with the torsion angles determined from the $^3J$ values (eq 1) being constrained. The AM1 calculations were performed with the MOPAC package, version 3.10, of J. J. P. Stewart[21] on a HITAC M280/200H computer at the computer center of this university. The perspective views of the optimized structures were drawn by the ORTEP II program.[22]

## Results

**Synthesis of Cobalt(III)–*N*-Glycoside Complexes.** We have attempted to obtain Co(III)–*N*-glycoside complexes from the reaction of aldoses with mononuclear Co(III) complexes such as $[Co(en)_3]^{3+}$, $[Co(H_2O)_2(en)_2]^{3+}$, and *cis*- and *trans*-$[CoCl_2(en)_2]^+$. However, all attempts failed under reflux conditions in methanol in the absence of additional reagent. In contrast, $[(en)_2Co(O_2)(OH)Co(en)_2]^{3+}$ reacted with aldoses in methanol without any additional reagent as described in method 2 to yield a series of novel Co(III) complexes containing an *N*-glycoside ligand, viz., D-Man-en, L-Rha-en, and D-Rib-en. Method 1 was more convenient as an adequate scale reaction than method 2 because of the low solubility of the binuclear complex in methanol. The purification of the major products was achieved by column chromatography (Dowex 50W-X8 cation-exchange resin). However, the yields of the *N*-glycoside complexes were considerably low (2.1–0.9%); the major loss being due to the formation of a large amount of brownish species which strongly adsorbed to SP-Sephadex C-25 resin.

**Characterization of Isolated Complexes.** The analytical data of the isolated complexes indicate that each Co(III) complex has one en ligand and one *N*-glycoside ligand derived from en and an aldose, and that the crystals of **1** contain sodium in amounts equimolar with the complex ion. The molar conductivity of **1** in aqueous solution is 204 $\Omega^{-1}$ cm$^2$ mol$^{-1}$, which is reasonable for the formation of a 2-mol quantity of 1:1 electrolyte from a 1-mol

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[17] $\Delta X_i$ values are given by $\Delta X_i = X_i - X_H$, where $X_i$ and $X_H$ are the electronegativity of the substituent atom i and hydrogen, respectively. The Huggins electronegativity[15] was used for H, C, N, and O. The electronegativity of Co was allowed to be equal to that of H.

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[21] A HITAC version was converted from the VAX version MOPAC86 (version 3.10) supplied from J. J. P. Stewart, Frank J. Seiler Research Laboratory, USAF Academy, Colorado Springs, Co.

[22] Johnson, C. K. ORTEP: A Fortran Thermal-Ellipsoid Plot Program for Crystal Structure Illustrations; USAEC Report ORNL-3794, revised 1965; overlap correction, 1971.

**Table I.** $^{13}C$ NMR Spectral Data Observed in $D_2O$

| complex | $\delta_C$, ppm[a] sugar unit | | | | | | en units | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 96.56 | 86.77 | 82.08 | 75.20 | 71.66 | 64.28 | 52.65 | 45.65 | 45.58 | 44.56 |
| **2** | 97.70 | 88.57 | 87.52 | 76.07 | 69.04 | 21.70 | 53.61 | 46.70 | 46.18 | 45.39 |
| **3** | 97.76 | 91.19 | 87.43 | 77.02 | 63.91 | | 53.77 | 46.40 | 45.91 | 45.44 |

[a] Chemical shifts are determined with reference to the 2-methyl-2-propanol signal at $\delta = 31.9$ ppm.

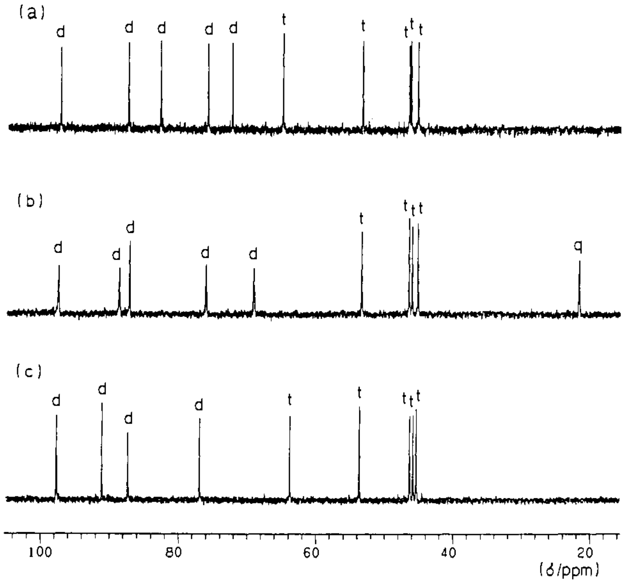

**Figure 1.** Low-power broad-band proton-decoupled $^{13}C$ NMR spectra observed in $D_2O$ after NH proton exchange: (a) Δ-[Co(D-Man-en)(en)]$^+$ (**1**); (b) Λ-[Co(L-Rha-en)(en)]$^+$ (**2**); (c) Λ-[Co(D-Rib-en)(en)]$^+$ (**3**). The multiplicities of the signals in the homo-gated proton-decoupled spectra are given by d = doublet, t = triplet, and q = quartet.

sample. The molar conductivity values of **2** and **3** are 106 and 93 $\Omega^{-1}$ cm$^2$ mol$^{-1}$, respectively, which fall within the range for those of 1:1 electrolytes.

Low-power broad-band proton-decoupled $^{13}C$ NMR spectra of the complexes in $D_2O$ are shown in Figure 1, and the spectral data are summarized in Table I. In each spectrum, four $^{13}C$ signals observed in the region of 44–55 ppm are assigned to the carbon atoms of the two en units on the basis of their chemical shifts and the fact that they appear as triplets in the homo-gated proton-decoupled spectrum. In each case, remarkably, one of the four signals appears at 7–8 ppm downfield from the other three. According to the reported tendency of the chemical shifts of methylene carbons adjacent to various types of coordinated amino groups,[23] $^{13}C$ signals from carbon atoms adjacent to a secondary NH group commonly appear at lower field than those adjacent to a primary $NH_2$ group. Hence, the $^{13}C$ signals in the vicinity of 53 ppm presumably correspond to the carbon atoms adjacent to the glycosidic NH groups. These observations suggest the formation of the *N*-glycoside bond between en and an aldose.

Figure 2 illustrates AB and CD spectra of the three complexes in aqueous solution, and the spectral data are summarized in Table II. The AB spectra closely resemble each other, and they have two main peaks in the d–d transition region. Each lowest energy peak shows a symmetrical curve with no shoulder in the first absorption region; the absorption maximum is in the range 19400–19500 cm$^{-1}$. The absorption maximum of each peak in the second absorption region appears in the range 26800–26900 cm$^{-1}$. These observations are typical for the *cis*-(O–O)–$N_4O_2$–Co(III)-type system.[24] The CD curves of **2** and **3** closely resemble each other and are approximately mirror images of that of **1**. **1** shows two negative peaks in the first absorption region, while both **2** and **3** show two positive peaks in the same region. From the empirical rule on the CD signs in this region and from comparison with the CD signs of optically active *cis*-(O–O)–[Co(O)$_2$-(en)$_2$]$^+$-type complexes in this region,[25] **1** can be assigned as the Δ-configuration and **2** and **3** as the Λ-configuration.

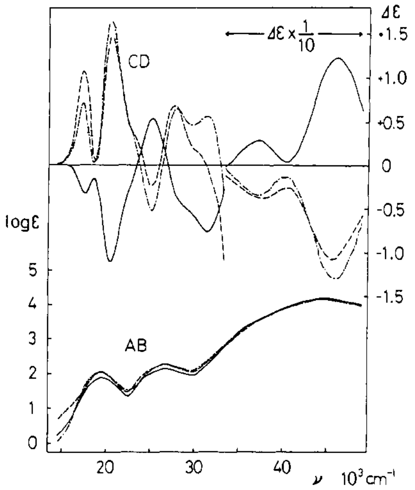

**Figure 2.** Electronic absorption (AB) and circular dichroism (CD) spectra: —, Δ-[Co(D-Man-en)(en)]$^+$ (**1**); -·-, Λ-[Co(L-Rha-en)(en)]$^+$ (**2**); ---, Λ-[Co(D-Rib-en)(en)]$^+$ (**3**).

**Table II.** Electronic Absorption (AB) and Circular Dichroism (CD) Spectral Data

| complex | AB max, $10^3$ cm$^{-1}$ (log ε) | CD max, $10^3$ cm$^{-1}$ (Δε) |
|---|---|---|
| Δ-[(D-Man-en)(en)]-$ClO_4 \cdot NaClO_4 \cdot 1.5H_2O$ (**1**) | 19.5 (1.89) | 17.5 (−0.34) |
| | | 20.4 (−1.12) |
| | | 22.8 (sh) (−0.14) |
| | 26.9 (2.12) | 25.2 (+0.54) |
| | | 28.2 (sh) (−0.42) |
| | | 31.5 (−0.77) |
| | 44.8 (4.19) | 37.2 (+2.92) |
| | | 46.0 (+12.39) |
| Λ-[Co(L-Rha-en)(en)]-$Br_2 \cdot H_2O$ (**2**) | 19.4 (2.01) | 17.3 (+0.71) |
| | | 20.4 (+1.65) |
| | | 22.9 (sh) (+0.34) |
| | 26.9 (2.26) | 25.1 (−0.52) |
| | | 27.9 (+0.65) |
| | | 31.3 (+0.57) |
| | 44.8 (4.13) | 36.9 (−3.46) |
| | | 45.9 (−12.85) |
| Λ-[Co(D-Rib-en)(en)]-$ClO_4 \cdot 2H_2O$ (**3**) | 19.4 (2.00) | 17.4 (+1.09) |
| | | 20.5 (+1.46) |
| | | 23.0 (sh) (+0.36) |
| | 26.8 (2.23) | 25.1 (−0.25) |
| | | 27.6 (+0.68) |
| | | 30.0 (sh) (+0.17) |
| | 44.8 (4.15) | 37.6 (−3.79) |
| | | 45.5 (−10.85) |

$^1H$ NMR spectra of the complexes observed in $D_2O$ after NH proton exchange show signals originated from protons that are attached to the carbon atoms of the sugar units and the en units.

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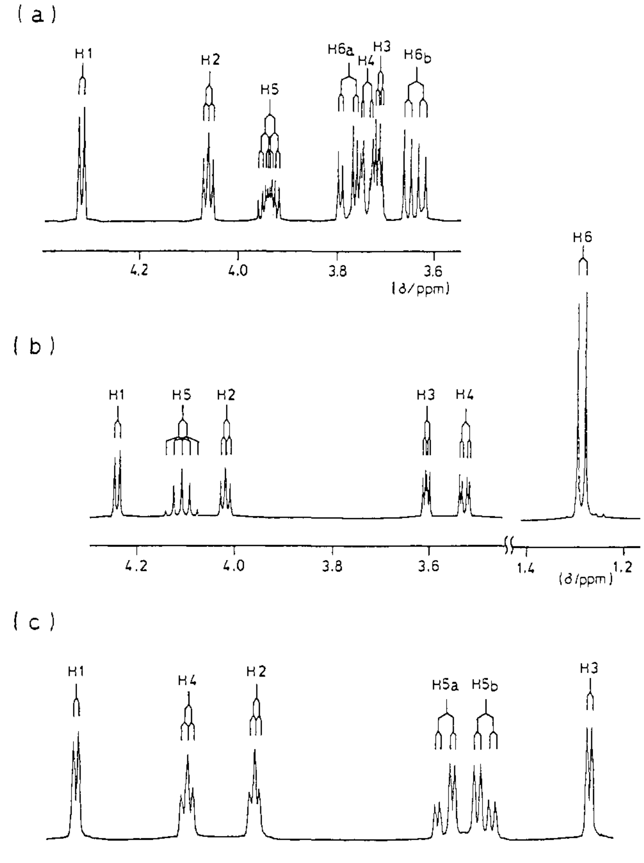

**Figure 3.** $^1H$ NMR signals from sugar units observed in $D_2O$ after NH proton exchange and their assignements: (a), Δ-[Co(D-Man-en)(en)]$^+$ (**1**); (b), Λ-[Co(L-Rha-en)(en)]$^+$ (**2**); (c), Λ-[Co(D-Rib-en)(en)]$^+$ (**3**).

**Table III.** $^1H$ NMR Chemical Shifts[a] ($\delta_H$/ppm) and $^1H$-$^1H$ Spin-Spin Coupling Constants ($^3J_{HH}$, $^2J_{HH}$/Hz) for Sugar Units Obtained from FT 400-MHz $^1H$ NMR Spectra[b]

| parameter | complex 1 | complex 2 | complex 3 |
|---|---|---|---|
| $\delta_{H1}$ | 4.325 | 4.243 | 4.332 |
| $\delta_{H2}$ | 4.065 | 4.021 | 3.959 |
| $\delta_{H3}$ | 3.715 | 3.607 | 3.277 |
| $\delta_{H4}$ | 3.741 | 3.527 | 4.098 |
| $\delta_{H5}$ | 3.940 | 4.108 | 3.570 (H5a)<br>3.487 (H5b) |
| $\delta_{H6}$ | 3.780 (H6a)<br>3.640 (H6b) | 1.287 | |
| $^3J_{1,2}$ | 4.3 | 4.3 | 4.0 |
| $^3J_{2,3}$ | 3.5 | 3.5 | 4.0 |
| $^3J_{3,4}$ | 2.1 | 2.1 | 0.0 |
| $^3J_{4,5}$ | 7.8 | 6.1 | 4.0 ($^3J_{4,5a}$)<br>5.3 ($^3J_{4,5b}$) |
| $^3J_{5,6}$ | 3.4 ($^3J_{5,6a}$)<br>5.8 ($^3J_{5,6b}$) | 6.7 | |
| $^2J_{HH}$ | 11.9 ($^2J_{6a,6b}$) | | 12.3 ($^2J_{5a,5b}$) |

[a] Chemical shifts are given relative to the internal standard TSP-$d_4$. [b] Digital resolution is 0.0008 ppm, 0.3 Hz.

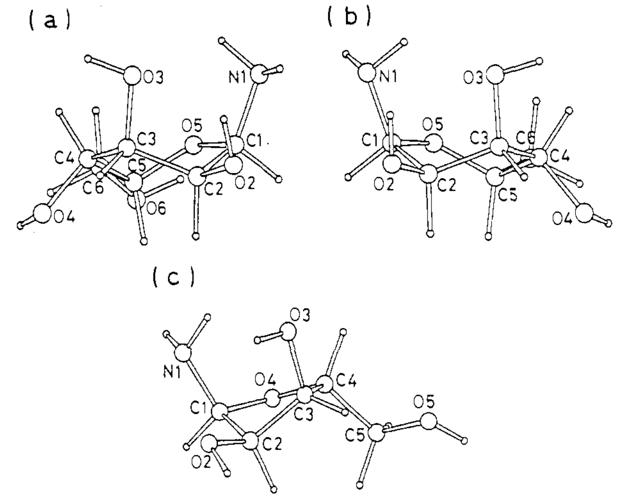

**Figure 4.** Perspective views of final structures of sugar units with numbering schemes for non-hydrogen atoms: (a), *N*-D-Man; (b), *N*-L-Rha; (c), *N*-D-Rib. Hydrogen atoms are drawn with smaller radii.

**Table IV.** Calculated Torsion Angles[a] ($\phi$/deg)

| fragment | sugar unit *N*-D-Man | sugar unit *N*-L-Rha | sugar unit *N*-D-Rib |
|---|---|---|---|
| H1-C1-C2-H2 | -39.3 | 39.3 | 58.0 |
| H2-C2-C3-H3 | 51.8 | -51.8 | -48.0 |
| H3-Co-C4-H4 | 105.4 | -105.4 | -89.0[b] |
| H4-C4-C5-H5 | -153.7 | 148.5 | *c* |

[a] Signs of torsion angles are defined according to ref 16. [b] Since eq 1 for $^3J_{3,4}$ of the *N*-D-Rib unit cannot hold for $^3J_{3,4} = 0$, the torsion angle is given for the minimum $^3J_{3,4}$ value (0.7822 Hz) in the equation. [c] Since the C5 methylene is out of the ring of the assumed furanose structure, the coordinates of the C5 carbon and the H5 methylene protons are exempt from eq 1 and 2, and they are optimized by the AM1 calculations.

For each complex, the latter signals appear as multiplets with 8 H integral gain in the region of 2.5–3.2 ppm. In contrast, the $^1H$ signals from the sugar units are as shown in Figure 3, which were fully assigned by employing the double- and triple-resonance techniques. The signals were analyzed as first-order patterns. The chemical shift values and $^1H$–$^1H$ spin–spin coupling constant values are listed in Table III. The obtained vicinal coupling constant values are remarkably different from those of free aldoses, which take the pyranose form in the usual chair conformation. In particular, the $^3J_{3,4}$ in **3** is 0.0 Hz. The $^3J_{3,4}$ values in **1** and **2** are also extremely small (2.1 Hz), while those in free D-Man and L-Rha are in the range 9.4–9.6 Hz in agreement with the trans coupling.[26] These results suggest that the structures of the sugar units on the complexes are different from those in the free aldoses.

**Conformational Analysis of Sugar Units.** The vicinal coupling constants converted into torsion angles of the H–C–C–H fragments on the rings of the *N*-D-Man, *N*-L-Rha, and *N*-D-Rib units, by using eq 1 and 2. A reasonable set of torsion angles for each ring structure is listed in Table IV. As a tool in the examination of the optimum conformation of the sugar units, semiempirical AM1 calculations[20] have been performed under the constraints of the thus determined torsion angles. The calculations gave optimized structures with heats of formation −239.1, −195.7, and−181.1 kcal mol$^{-1}$, for *N*-D-Man, *N*-L-Rha, and *N*-D-Rib, respectively. The bond lengths and angles in the final structures are normal.[27] The perspective views of the final structures are drawn in Figure 4. Both the *N*-D-Man and *N*-L-Rha units take the $^3S_5$ skew-boat conformation, while the *N*-D-Rib unit adopts the $^2E$ envelope conformation.

## Discussion

It was found that $[(en)_2Co(O_2)(OH)Co(en)_2]^{3+}$ can react with aldoses under mild conditions to give Co(III)–*N*-glycoside complexes. The novel reactivity of the binuclear Co(III) complex seems to be due to its substitution lability, as the en ligands can be substituted by propylenediamine in aqueous solution[28] unlike the case of the mononuclear Co(III) complexes. The reaction of method 1 using $CoCl_2 \cdot 6H_2O$ as starting cobalt species seems to

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(26) Altona, C.; Haasnoot, C. A. G. *Org. Magn. Reson.* **1980**, *13*, 417–429.

(27) Bond lengths are as follows: For C–C, 1.52–1.57 Å; for C–O, 1.40–1.45 Å; for C–N, 1.44–1.45 Å; for C–H, 1.11–1.14 Å; for O–H, 0.96–0.97 Å; for N–H, 1.00–1.01 Å. All bond angles are in the range 100.3–118.3°.

(28) Sasaki, Y.; Fujita, J.; Saito, K. *Bull. Chem. Soc. Jpn.* **1971**, *44*, 3373–3378.

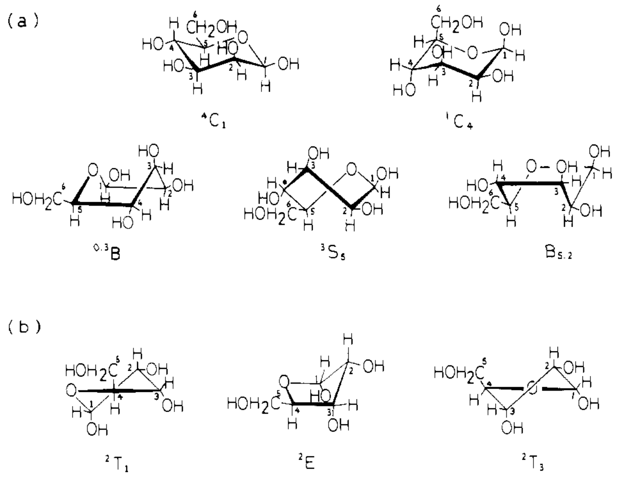

**Figure 5.** (a) Some conformations of β-D-mannopyranose. $^4C_1$ and $^1C_4$ are typical chair conformations. Skew-boat and boat conformations are interconverted; the $^3S_5$ skew-boat form occurs between the $^{0,3}B$ and $B_{5,2}$ boat forms. (b) Some conformations of α-D-ribofuranose. Envelope and twist conformations are easily interconverted; the $^2E$ envelope conformation occurs between two twist forms ($^2T_1$ and $^2T_3$).

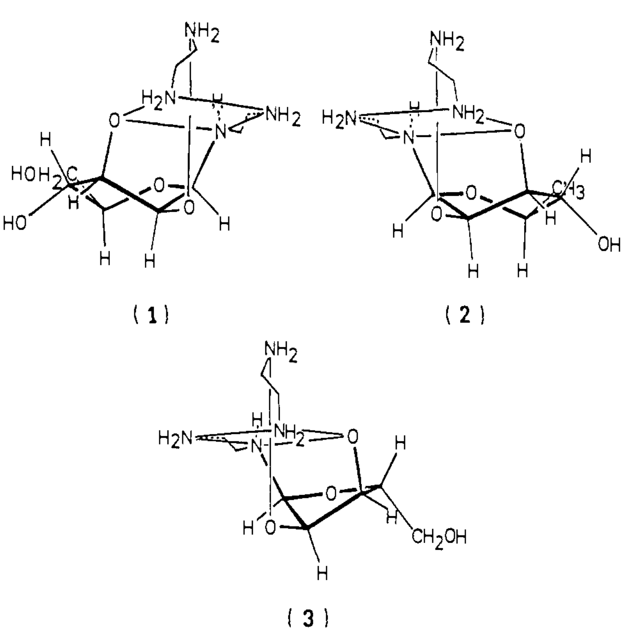

**Figure 6.** Structures of Δ-[Co(D-Man-en)(en)]$^+$ (**1**), Λ-[Co(L-Rha-en)(en)]$^+$ (**2**), and Λ-[Co(D-Rib-en)(en)]$^+$ (**3**).

be essentially the same as that of method 2. Thus, the binuclear Co(III) complex, which is easily formed by the oxidation of Co(II) to Co(III) in the presence of en,[15] presumably plays an important role as a reactive complex with aldoses.

The characterization by elemental analysis, conductivity measurements, and AB, CD, and $^{13}C$ NMR spectroscopies has clarified the composition of the Co(III)-*N*-glycoside complexes and has provided useful information to elucidate their structures. Consequently, it is indicated that each complex ion is composed of a bidentate en ligand and a tetradentate *N*-glycoside ligand derived from an en molecule and an aldose, and that the *N*-glycoside ligand binds to the Co atom through the two N atoms and the two O atoms. According to the literature regarding Co(III) amino alcohol complexes,[29] hydroxyl groups at the metal-binding sites are commonly subject to deprotonation of their hydroxyl protons in neutral solution. Conversely, the *N*-glycoside complex ions behave as singly charged cations in neutral aqueous solution. From analogy with amino alcohol complexes, each *N*-glycoside ligand presumably binds to the Co atom through its two deprotonated hydroxyl oxygens.

**Table V.** Selected Interatomic Distances ($r$/Å) in Final Structures of Sugar Units

| sugar unit | $r$(N1,O2) | $r$(N1,O3) | $r$(O2,O3) |
|---|---|---|---|
| *N*-D-Man | 2.86 | 2.98 | 2.82 |
| *N*-L-Rha | 2.86 | 2.97 | 2.78 |
| *N*-D-Rib | 2.92 | 2.88 | 2.86 |

In the previous paper,[14] the discussion about the structures of the sugar units was based on the qualitative conformational analysis, in which the torsion angles of the H-C-C-H fragments in the sugar rings were estimated by the qualitative application of the Karplus equation[30] and the ring structures were optimized by use of the scale models. This time, we have attempted to elucidate the structures of the sugar units by means of a more quantitative method of conformational analysis, i.e., a method combining the quantitative estimation of the torsion angles from $^1H$ NMR $^3J$ coupling constants with the geometry optimization by MO calculations under the constraints imposed from the estimated torsion angles. In such a treatment, it may be indispensable to consider the influence of electronegative substituents upon the $^3J$ values, which are characteristic of sugars. As a method of the estimation of the torsion angles, therefore, we have adopted the empirical equation of Haasnoot et al.[16] including a correction term for the electronegativity and the relative position of the substituents attached to the H-C-C-H fragment, which is known to accurately reproduce vicinal $^1H$–$^1H$ spin–spin coupling constants observed in sugar derivatives[31] and proline derivatives.[32] As a method for the optimization of the sugar unit structures, we have employed the semiempirical AM1 method[20] because it has the ability to successfully reproduce hydrogen bonds and experimental data for species containing N and/or O atoms.

Pyranose rings can adopt various conformations: chair, boat, and skew-boat forms, some of which are illustrated in Figure 5 (a). Free mannopyranose and rhamnopyranose take the $^4C_1$ chair conformation as the most stable structures.[33] Interestingly, the results of the present conformational analysis indicate that the *N*-D-Man and *N*-L-Rha units take the unusual $^3S_5$ skew-boat conformation as estimated by the previous qualitative conformational analysis.[14]

It is generally difficult to estimate the conformation of a furanose ring since it can adopt various conformations with slight structural difference: envelope and twist forms (Figure 5b).[33] In the case of the *N*-D-Rib, it is very difficult to discriminate between the $^2T_3$ twist and $^2E$ envelope forms. The present calculations lead to the conclusion that the $^2E$ envelope conformation is the optimum structure.

The coordination structures of the sugar units have been discussed on the basis of the optimized structures of the sugar units. If the Co(III) complexes are ideally octahedral structures and the bond lengths between the central Co atom and the donor atoms are 2.00 Å, interatomic distances between the donor atoms facially binding to the Co atom are expected to be 2.83 Å. Interatomic distances between N1 and O2, O2 and O3, and O3 and N1 in the final structures of the three sugar units are listed in Table V. The interatomic distances are in the range 2.78–2.97 Å and are thus reasonable for the facial binding of the sugar units through the three donor atoms. The facial binding structures seem to be the only ones that can be consistent with the fact that the *N*-glycoside ligands act as tetradentate chelates with two donors and two O donors. Thus, the structures of the complex ions can be

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(29) (a) Bertrand, J. A.; Eller, P. G. *Prog. Inorg. Chem.* **1977**, *21*, 29–53. (b) Wardeska, J. G.; Clearfield, A.; Troup, J. M. *Inorg. Chem.* **1979**, *18*, 1641–1648. (c) Clearfield, A.; Rudolf, P.; Wardeska, J. G. *Ibid.* **1983**, *22*, 2713–2716.

(30) Karplus, M. *J. Chem. Phys.* **1959**, *30*, 11–15; *J. Am. Chem. Soc.* **1963**, *85*, 2870–2871.

(31) De Leeuw, F. A. A. M.; Altona, C. *J. Chem. Soc., Perkin Trans. 2* **1982**, 375–384.

(32) Haasnoot, C. A. G.; De Leeuw, F. A. A. M.; De Leeuw, H. P. M.; Altona, C. *Biopolymers* **1981**, *20*, 1211–1245.

(33) Stoddart, J. F. *Stereochemistry of Carbohydrates*; Wiley-Interscience: New York, 1971.

concluded as shown in Figure 6. L-Rha is just a mirror image of D-Man except for the replacement of a hydroxyl group on C6 by hydrogen. The structures of **1** and **2** are approximately mirror images of each other. Although D-Rib is a D-type aldose, the chelate skeleton structures and the absolute configuration of the asymmetric nitrogen of **3** are similar to those of **2**. These structural features seem to be in accordance with the CD spectral features.

Interestingly, the coordination behavior of *N*-glycosides formed from en and aldoses in the substitution-inert Co(III) system is greatly different from that in the substitution-labile Ni(II) systems[7,8] as follows: (i) The Co(III) complexes contain only one *N*-glycoside ligand. (ii) The sugar units bind to the Co atom at the three points of the donor atoms on C1, C2, and C3. (iii) The metal bindings induce structural changes in the sugar units.

The three-point binding through donor atoms on C1, C2, and C3 plays an essential role in terms of the polynuclear structure exhibited by the calcium complex with $\beta$-D-mannofuranose.[3] The same mode of binding is observed in the binuclear Ni(II) complex containing a $\beta$-D-mannofuranose derivative.[11] The stabilization of these complexes seems to be due to the binding of the metal–metal centers supported by the hydroxyl oxygens of the substituent group on C4. However, in the substitution-inert Co(III) complexes, their strong coordination bonds and the tetradentate chelation effects presumably contribute to the stabilization of the mononuclear complexes. In addition, Angyal et al. have reported the three-point interaction between alkaline-earth-metal ions and aldoses in aqueous solution.[2] It is of interest that the three-point binding is important in both the transition- and non-transition-metal complex systems; this contributes to a greater understanding of the interaction between metal ions and sugars.

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# Cadmium Sulfide Mediated Photoelectric Effects in Bilayer Lipid Membranes

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**Abstract:** Cadmium sulfide (CdS) particles, in situ generated on one side of glyceryl monooleate (GMO) bilayer lipid membranes (BLMs), have been used to mediate photoelectric effects. Steady-state and time-resolved photovoltage measurements have been carried out as functions of the wavelength and intensity of irradiation; variable current drain (external resistance); added electron donors and acceptors like methylviologen ($MV^{2+}$), $K_2PtCl_6$, $CuCl_2$, $KMnO_4$, $NaHSO_3$, $Na_2S_2O_5$, and $KI_3$; and the amount of oxygen present in the solution bathing the BLM. Steady-state illumination of a CdS-containing BLM resulted in the prompt development of −150 to −200 mV (the CdS or the cis side being negative) potential difference in an open circuit across the GMO BLM. This initial photovoltage, $V_I$, quickly decayed to a steady value, $V_S$ (−100 to −150 mV). When the illumination was turned off, the potential difference across the GMO BLM decreased to its dark value in 3–4 min. Both $V_I$ and $V_S$ increased with increasing light intensities to saturation levels and produced action spectra corresponding to that of bulk crystalline CdS. Decreasing the concentration of oxygen in the solution bathing the BLM (by the addition of glucose, glucose oxidase, and catalase or by argon bubbling) reduced both $V_I$ and $V_S$. Addition of electron scavengers to the cis side of the BLM increased the photovoltage. Conversely, photovoltage was reduced by the addition of hole scavengers to the cis side or by the removal of $SH^-$ or $H_2S$ from the side opposite to CdS (the trans side) of the BLM. Excitation of the CdS-containing GMO BLM by 20 ns, 353.4 nm laser pulses resulted in a transient photovoltage signal whose buildup fitted a single exponential ($t_{1/2} \sim 235 \pm 15$ ns) and whose decay could be resolved into a faster (complete within 40 μs) and a slower (complete within 1–2 s) component. The effect of additives was qualitatively similar to those observed in steady-state illuminations. Good linear current–applied voltage behavior was observed for the CdS GMO BLM both in the dark and under constant illumination. Slopes of these plots, 1.6 and 4.6 pA/mV, gave $6.3 \times 10^8$ and $2.2 \times 10^8$ ohms resistances in the dark and under illumination, respectively. The observed photoelectric effects have been rationalized in terms of equivalent circuits and chemical reactions. The chemical reactions included the following: band gap excitation of CdS to produce conduction band electrons, $e_{CB}^-$, and valence band holes, $h_{VB}^+$; reactions of trapped electrons, $e_{CB(t)}^-$, with oxygen at the semiconductor water interface ($O_{2(i)} + e_{CB(t)}^- \rightarrow O_2{}^{\bullet -}{}_{(i)}$); the diffusion of $O_2{}^{\bullet -}{}_{(i)}$ to the solution ($O_2{}^{\bullet -}{}_{(i)} + O_{2(s)} \rightarrow O_2{}^{\bullet -}{}_{(s)} + O_{2(i)}$); and oxidation of $H_2S$ or $SH^-$ by trapped holes, $h_{VB(t)}^+$ ($H_2S + h_{VB(t)}^+ \rightarrow HS^\bullet + H^+$ and/or $SH^- + h_{VB(t)}^+ \rightarrow HS^\bullet$). Thus, generation of $O_2{}^{\bullet -}$ in the cis and $H^+$ in the trans side of the solution bathing the CdS GMO BLM is the net consequence of bandgap excitation and the appearance of photovoltage is the result of vectorial transfer of charges in the direction opposite to and enhanced by the asymmetric membrane potential. Photovoltage decay is ascribed to charge recombination via mass transport of the ions through the BLM. These results have been compared to those reported previously on using "pigmented" BLMs.

A bimolecular thick membrane, a BLM, physically separates two aqueous solutions.[1,2] In the absence of additives or fortuitous impurities, the BLM is an excellent electrical insulator. Incorporation of ionophores or reconstitution of transport proteins into BLMs has increased ion conductivities across the membranes.[3-5] Sensitive electrical measurements in these systems have significantly contributed to our current understanding of the biological transport mechanisms.[6]

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