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Model for the Binding of D-Penicillamine to Metal Ions in Living Systems: Synthesis and Structure of L-Histidinyl-D-penicillaminatocobalt(III) Monohydrate, [Co(L-His)(D-Pen)]·H_2O

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Abstract: The complex L-histidinyl-D-penicillaminatocobalt(III) monohydrate, $C_{11}H_{19}N_4O_5SCo$, has been synthesized and its crystal structure has been determined from three-dimensional x-ray diffractometer data. The crystals are monoclinic, space group $P2_1$, with two molecules in a cell of dimensions a = 7.078 (2), b = 12.263 (4), c = 8.856 (3) Å, and β = 96.06 (2)°. Full-matrix least-squares refinement using 2185 independent intensities (Mo Kα radiation) has yielded a conventional R factor of 0.032. The structure consists of monomeric Co(L-His)(D-Pen) units and water molecules. The penicillamine ligand coordinates to the metal as the dianion, with Co–S, Co–N, and Co–O bonds of length 2.281 (1), 1.973 (4), and 1.921 (1) Å, respectively. The histidine monoanion coordinates through Co–N(amino), Co–N(imidazole), and Co–O bonds of length 1.933 (3), 1.925 (3), and 1.989 (3) Å, respectively. The geometry at cobalt is distorted octahedral, with cis bond angles in the range 82.6 (1)–98.3 (2)°. It is noteworthy that the diastereomeric complex Co(L-His)(L-Pen) cannot be isolated using the same synthetic technique, and that addition of D,L-histidine and D,L-penicillamine to solutions of cobalt(II) salts lead only to the title complex and its enantiomer.

Metal poisoning, produced largely by industrial pollution[1] but also by the widespread use of metal and organometallic complexes in appliances and agriculture,[2] has become a focus of general concern in both industrialized and advanced agricultural societies.[3] It is well established that the administration of some organic chelating agents is of therapeutic value. Two of the more commonly employed agents contain sulfur atoms, these being BAL (2,3-dimercaptopropanol) and D-penicillamine (β,β-dimethyl-D-cysteine), while some (e.g., EDTA and its analogues) do not. While BAL has been found to be useful,[4] its administration to patients must be carefully monitored since BAL is itself toxic; such problems do not arise if D-penicillamine is used, although it is noteworthy that its enantiomer is toxic.

Largely as a consequence of this biological significance, but also in part as a result of a general interest in metal–peptide complexes as models for metalloenzymes, the structural chemistry of metal complexes of cysteine and penicillamine has received recent attention in a number of laboratories.[5-17] It is apparent from this work that, while tridentate coordination by cysteine and its derivatives is possible, it is not universal.

Since in the living system the toxic metal ions bind to peptide residues of proteins, we felt that complexes which contain metal ions coordinated to both an L-amino acid and D-Pen may be better models for the therapeutic action of D-Pen than are its complexes of the free metal ions. Since metal ions in a variety of metalloenzymes coordinate to histidyl residues, we chose L-histidine as our L-amino acid residue. We here report the synthesis and structure of the first fully characterized complex of the general type M(AA)(D-Pen) [where AA is an amino acid], the complex studied being [Co(L-His)(D-Pen)].

Experimental Section

Synthesis. L-Histidine (0.002 mol in 15 ml of water) was added to 0.001 mol of cobalt(II) chloride dissolved in 5 ml of water. To this solution was added 0.001 mol of D-penicillamine. The solution becomes progressively darker in color, changing from its original pale orange to deep brown over a period of 24 h; this color change is associated with the oxidation of cobalt(II) to cobalt(III). After several hours, dark prismatic crystals of the title compound formed. Substitution of D,L-penicillamine for D-penicillamine also produces the color change, but yields only crystals of the title complex, and substitution of D-histidine for L-histidine yields no isolable penicillamine containing complex, despite changing color from orange to brown. It is noteworthy, however, that electronic spectra of the reaction mixtures demonstrate that the complex Co(D-His)(D-Pen) [or its enantiomer Co(L-His)(L-Pen)] is formed in aqueous solution using either of these techniques; apparently, it is much more soluble than the diastereomeric material Co(L-His)(D-Pen).

Collection and Reduction of the X-Ray Data. On the basis of Weissenberg and precession photographs, the crystals were assigned to the monoclinic system. The observed systematic absences are $0k0$ for k odd, which suggests that the space group is $P2_1$ ($C_{2h}{}^5$). The cell constants, obtained by least-squares methods,[18] are a = 7.078 (2), b = 12.263 (4), c = 8.856 (3) Å, and β = 96.06 (2)°. The observations were made at 20.5° with the wavelength assumed as λ(Mo Kα_1) = 0.7093 Å. A density of 1.643 g cm^{-3} calculated for two formula units in the cell compares well with a value of 1.60 (2) g cm^{-3} observed by flotation in bromoform/carbon tetrachloride solution. Hence, in space group $P2_1$, no crystallographic symmetry is imposed on the molecules.

Diffraction data were collected on a Picker Facs-I diffractometer from a crystal with faces (010), $(0\bar{1}\bar{1})$, $(0\bar{1}1)$, $(\bar{1}00)$, (100), and $(11\bar{1})$, which represents one of the two typical morphologies of this complex which we have observed.

Many crystals which were examined were found to be twinned, but

Table I. Fractional Coordinates with Standard Deviations in Parentheses

Atom	*X*	*Y*	*Z*
Co	0.14757 (6)	¼	0.20972 (5)
S	0.0823 (2)	0.3585 (1)	0.0091 (1)
N(1)	0.4176 (5)	0.2786 (3)	0.2265 (4)
C(1)	0.4886 (5)	0.2636 (4)	0.3893 (4)
C(2)	0.4595 (6)	0.3676 (4)	0.4785 (5)
C(3)	0.3809 (6)	0.1697 (3)	0.4545 (4)
C(4)	0.2596 (6)	0.4077 (3)	0.4608 (4)
C(5)	0.1818 (7)	0.4866 (3)	0.5413 (5)
C(6)	−0.0346 (6)	0.4230 (4)	0.3658 (5)
N(2)	0.1231 (5)	0.3676 (3)	0.3503 (4)
N(3)	−0.0051 (6)	0.4958 (3)	0.4794 (4)
O(1)	0.2215 (5)	0.1455 (3)	0.3773 (3)
O(2)	0.4443 (6)	0.1264 (3)	0.5738 (4)
O(3)	−0.1146 (4)	0.2110 (3)	0.2140 (3)
O(4)	−0.3492 (4)	0.1285 (3)	0.0735 (4)
N(4)	0.1394 (5)	0.1313 (3)	0.0589 (4)
C(7)	−0.1859 (5)	0.1621 (3)	0.0929 (4)
C(8)	−0.0485 (6)	0.1499 (3)	−0.0278 (4)
C(9)	−0.0400 (7)	0.2573 (4)	−0.1195 (4)
C(10)	0.0712 (21)	0.2384 (6)	−0.2554 (9)
C(11)	−0.2387 (12)	0.2993 (6)	−0.1736 (9)
W[a]	0.4468 (6)	0.0073 (4)	−0.1555 (4)
H(1)	0.438 (7)	0.332 (5)	0.206 (6)
H(2)	0.493 (8)	0.227 (5)	0.179 (6)
H(3)	0.613 (7)	0.245 (5)	0.413 (5)
H(4)	0.559 (8)	0.436 (5)	0.451 (6)
H(5)	0.512 (8)	0.354 (6)	0.572 (7)
H(6)	0.217 (8)	0.527 (5)	0.630 (6)
H(7)	−0.109 (7)	0.531 (5)	0.492 (5)
H(8)	−0.155 (7)	0.416 (5)	0.302 (5)
H(9)	0.139 (7)	0.069 (4)	0.099 (5)
H(10)	0.264 (10)	0.141 (6)	−0.032 (8)
H(11)	−0.056 (9)	0.085 (6)	−0.112 (7)
H(12)	0.083 (11)	0.310 (7)	−0.302 (8)
H(13)	0.171 (4)	0.200 (9)	−0.226 (11)
H(14)	−0.062 (16)	0.197 (12)	−0.340 (11)
H(15)	−0.269 (17)	0.371 (10)	−0.233 (12)
H(16)[b]	−0.309	0.245	−0.232
H(17)[b]	−0.308	0.311	−0.083
H(18)	0.480 (11)	0.055 (8)	−0.106 (9)
H(19)	0.441 (9)	0.062 (6)	−0.242 (8)

[a] The symbol W, here and elsewhere, represents the water oxygen atom. [b] Calculated positions.

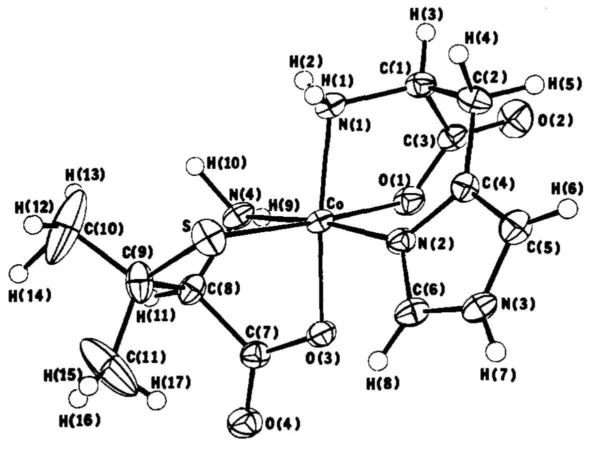

Figure 1. View of the [Co(L-His)(D-Pen)] molecule. Hydrogen atoms are represented by spheres of arbitrary size; thermal ellipsoids are drawn at the 40% probability level.

eventually a crystal was obtained whose ω-scans, while broader than we would have liked, were single. The crystal chosen had approximate dimensions 0.44 × 0.38 × 0.31 mm, and was mounted roughly parallel to the crystallographic *a* axis.

Intensity data were collected at a takeoff angle of 1.6°; at this angle the intensity of a typical reflection was approximately 75% of maximum as a function of takeoff angle. The receiving aperture was 5.0 mm high by 5.0 mm wide and was positioned 32.0 cm from the crystal. The data were collected by the θ–2θ scan technique at a scan rate of 1.0°/min. Allowance was made for the presence of both $K\alpha_1$ and $K\alpha_2$ radiations, the peaks being scanned from −1.1° in 2θ below the calculated $K\alpha_1$ peak position to 1.1° in 2θ above the calculated $K\alpha_2$ position. Stationary-counter, stationary-crystal background counts of 20 s were taken at each end of the scan. The pulse-height analyzer was set for approximately a 90% window, centered on the Mo$K\alpha$ peak.

A unique data set having $2° \leq 2\theta \leq 60°$ was gathered; a total of 2461 intensities were recorded. The intensities of three standard reflections, measured after every 100 reflections, showed no decline other than that predicted by counting statistics.

Data processing was carried out as described by Corfield et al.[19] After correction for background, the intensities were assigned standard deviations according to the formula[20]

$$\sigma(I) = [C + 0.25(\mathrm{ts}/\mathrm{tb})^2(\mathrm{BH} + \mathrm{BL}) + (pI)^2]^{1/2}$$

and the value of p was selected as 0.04. The values of I and $\sigma(I)$ were corrected for Lorentz and polarization effects and for absorption factors. The absorption coefficient for this compound for Mo $K\alpha$ radiation is 13.3 cm^{-1}, and for the crystal chosen the transmission coeffiiceints[21] evaluated by numerical integration ranged from 0.742 to 0.814. Of the 2461 data collected, 2185 were greater than 2.6 times their estimated standard deviations; only these data were used in the subsequent structure analysis and refinement.

Solution and Refinement of the Structure. The positions of the cobalt and sulfur atoms were determined from a three-dimensional Patterson function, and two cycles of least-squares refinement of this position were run. All least-squares refinements in this analysis were carried out on F, the function minimized being $\Sigma w(|F_o| - |F_c|)^2$ and the weights w being taken as $4F_o^2/\sigma^2(F_o^2)$. In calculations of F_c, the atomic scattering factors for Co, S, O, N, and C were from International Tables[22] and those for H from Stewart, Davidson, and Simpson.[23] The effects of the anomalous dispersion of Co and S were included in the calculation of F_c, the values of $\Delta f'$ and $\Delta f''$ being taken from Cromer and Liberman.[24] The remaining non-hydrogen atoms were located in subsequent difference Fourier maps. Isotropic least-squares refinement of these atoms led to values of the conventional agreement factors

$$R_1 = \Sigma||F_o| - |F_c||/\Sigma|F_o| \text{ and}$$

$$R_2 = [\Sigma w(|F_o| - |F_c|)^2/\Sigma w(F_o)^2]^{1/2}$$

of 0.073 and 0.101, respectively. Anisotropic refinement of these atoms gave $R_1 = 0.046$ and $R_2 = 0.068$. At this stage the coordinates (x,y,z) of all atoms were replaced by $(\bar{x},\bar{y},\bar{z})$; three cycles of least-squares refinement on this enantiomer converged to $R_1 = 0.049$ and $R_2 = 0.070$, which demonstrates that our original enantiomeric choice was the correct one. This enantiomeric assignment corresponds to the expected arrangement of histidine as the L isomer and penicillamine as the D isomer.

The positions of 17 of the 19 hydrogen atoms were located in a difference Fourier map. The two remaining hydrogen atoms, which are associated with one of the methyl groups of the penicillaminato ligand, were placed in positions calculated on the basis of tetrahedral geometry at the methyl carbon atom and C–H distances of 0.95 Å.[25] In the next refinement, all non-hydrogen atoms were refined anisotropically, the 17 hydrogen atoms were refined isotropically, and the two calculated hydrogen atoms were included in the refinement but not varied. This refinement gave the final values of $R_1 = 0.032$ and $R_2 = 0.047$. The final values of F_o and F_c suggested that no correction for secondary extinction was necessary. In the final cycle of least-squares refinement no parameter underwent a shift in excess of 38% of its estimated standard deviation, which is taken as evidence that the refinement had converged. A final difference Fourier synthesis was featureless, with no peak higher than 0.5 e Å^{-3} except for one of height 0.92 e Å^{-3} in the vicinity of the Co atom. The values of R_2 showed no unusual dependence on sin θ or on $|F_c|$.

The positional and thermal parameters derived from the final least-squares cycle are given in Tables I and II. A compilation of observed and calculated structure amplitudes is available.[26]

Table II. Thermal Parameters for [Co(L-His)(D-Pen)]H_2O

Atom	β_{11}[a]	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}	Atom	B, Å^2
Co	0.00794 (8)	0.00278 (3)	0.00657 (5)	0.00024 (5)	0.00237 (4)	−0.00005 (4)	H(1)	1.8 (1.0)
S	0.01844 (25)	0.00299 (5)	0.00998 (13)	−0.00032 (9)	−0.00102 (14)	0.00034 (7)	H(2)	3.1 (1.2)
N(1)	0.0100 (6)	0.0029 (2)	0.0085 (4)	0.0000 (2)	0.0028 (4)	0.0005 (2)	H(3)	2.4 (0.9)
C(1)	0.0087 (5)	0.0039 (3)	0.0088 (4)	0.0007 (3)	0.0017 (4)	0.0010 (3)	H(4)	2.0 (1.0)
C(2)	0.0110 (8)	0.0036 (3)	0.0100 (5)	−0.0004 (3)	−0.0002 (5)	0.0001 (3)	H(5)	3.4 (1.2)
C(3)	0.0107 (7)	0.0031 (2)	0.0083 (5)	0.0014 (3)	0.0024 (4)	0.0004 (2)	H(6)	3.4 (1.2)
C(4)	0.0114 (7)	0.0030 (2)	0.0066 (4)	−0.0005 (3)	0.0010 (4)	−0.0002 (2)	H(7)	2.3 (1.0)
C(5)	0.0157 (8)	0.0034 (2)	0.0087 (5)	−0.0002 (4)	0.0024 (5)	−0.0008 (3)	H(8)	2.3 (1.0)
C(6)	0.0112 (7)	0.0040 (2)	0.0096 (5)	0.0009 (4)	0.0030 (5)	−0.0006 (3)	H(9)	1.6 (0.8)
N(2)	0.0097 (6)	0.0034 (2)	0.0073 (4)	0.0003 (3)	0.0019 (4)	−0.0008 (2)	H(10)	0.7 (1.6)
N(3)	0.0119 (6)	0.0039 (2)	0.0098 (5)	0.0014 (3)	0.0036 (5)	−0.0007 (3)	H(11)	4.1 (1.3)
O(1)	0.0135 (6)	0.0042 (2)	0.0091 (4)	−0.0008 (3)	0.0029 (4)	0.0015 (2)	H(12)	4.7 (1.5)
O(2)	0.0217 (9)	0.0049 (2)	0.0117 (5)	0.0019 (4)	0.0022 (5)	0.0027 (3)	H(13)	6.9 (2.6)
O(3)	0.0095 (5)	0.0048 (2)	0.0075 (3)	−0.0007 (2)	0.0019 (3)	−0.0013 (2)	H(14)	10.3 (3.4)
O(4)	0.0123 (6)	0.0067 (3)	0.0118 (4)	−0.0020 (3)	0.0017 (4)	−0.0031 (3)	H(15)	11.9 (3.1)
N(4)	0.0115 (7)	0.0032 (2)	0.0097 (5)	0.0009 (3)	0.0041 (4)	−0.0001 (3)	H(16)	10.0
C(7)	0.0104 (7)	0.0034 (2)	0.0084 (4)	0.0001 (3)	0.0016 (4)	−0.0007 (3)	H(17)	10.0
C(8)	0.0136 (8)	0.0032 (2)	0.0073 (4)	−0.0006 (3)	0.0030 (5)	−0.0008 (2)	H(18)	6.5 (2.0)
C(9)	0.0242 (10)	0.0039 (2)	0.0067 (4)	−0.0013 (5)	−0.0001 (5)	0.0008 (3)	H(19)	3.7 (1.4)
C(10)	0.0837 (49)	0.0051 (5)	0.0145 (9)	−0.0050 (12)	0.0236 (19)	−0.0005 (6)		
C(11)	0.0345 (20)	0.0073 (5)	0.0251 (13)	−0.0056 (9)	−0.0182 (14)	0.0060 (7)		
W	0.0248 (10)	0.0058 (3)	0.0106 (5)	−0.0035 (4)	−0.0036 (5)	−0.0002 (3)		

[a] The form of the thermal ellipsoid is $\exp[-(\beta_{11}h^2 + \beta_{22}k^2 + \beta_{33}l^2 + 2\beta_{12}hk + 2\beta_{13}hl + 2\beta_{23}kl)]$.

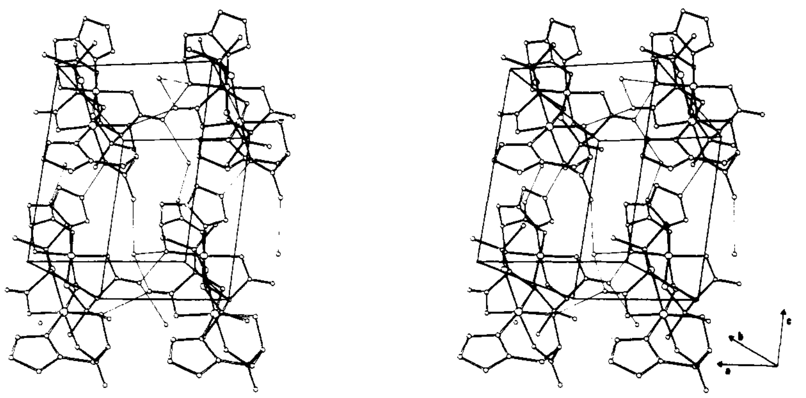

Figure 2. Stereoview of the packing and hydrogen bonding in the crystals of [Co(L-His)(D-Pen)]·H_2O.

Description of the Structure. The structure consists of discrete monomeric [Co(L-His)(D-Pen)] units which are hydrogen bonded to the water molecule. The structure of the complex is shown in Figure 1, and a view of the packing and hydrogen bonding is given in Figure 2.

The coordination around the cobalt(III) center is approximately octahedral, the ligands binding as the histidine monoanion and the penicillamine dianion. The metal coordinates to the histidyl residue through the amine [N(1)] and imidazole [N(2)] nitrogen atoms and through a carboxyl oxygen atom [O(1)] with bond lengths of 1.933 (3), 1.925 (3), and 1.989 (3) Å, respectively. This tridentate coordination by L-His is similar to that observed[27-32] in [Co(L-His)$_2$], [Ni(L-His)$_2$], [Co(L-His)(D-His)], [Mo_2O_4(L-His)$_2$], [$Mo_2S_2O_2$(L-His)], and in [Cu(L-His)(L-Thr)(OH_2)]; bidentate and mondentate coordination have also been observed for this ligand.[33-38] The geometry of the L-His residue is similar to that in the other tridentate complexes.[39] The bond angles subtended the histidine ligand at cobalt are N(1)-Co-O(1) = 83.1 (1)°, N(1)-Co-N(2) = 88.3 (1)°, and O(1)-Co-N(2) = 92.0 (1)°; the smallest angle is associated with the smallest (five-membered) ring, and the largest with the largest (seven-membered) ring.

The Pen^{2-} ion, which is deprotonated at the sulfur and carboxyl ends, coordinates to the metal through S, the amine nitrogen atom [N(4)], and the carboxyl oxygen atom [O(3)] with cobalt-ligand bond lengths of 2.228 (1), 1.973 (4), and 1.921 (3) Å, respectively. These distances can be compared to the average distances of 2.272 (2), 1.946 (6), and 1.906 (5) Å in the *S*-methyl-L-cysteinato (SMC) complex[16] [Co(SMC)$_2^+$], which suggest that the binding to N and O may be stronger in the latter complex. The bond angles at cobalt are S-Co-N(4) = 85.0 (1), S-Co-O(3) = 92.6 (1), and N(4)-Co-O(3) = 82.6 (1)°; here again, the largest bond angle is associated with the largest (six-membered) ring.

The tridentate coordination by D-Pen observed here is similar to that observed[13] in [Pb(D-Pen)], but is in contrast to its coordination in complexes of mercury(II)[9,10,12] and cadmium(II);[14] similarly, while tridentate coordination by cysteine and its other derivatives has been observed,[5-17] it is not found in the majority of structures which have been determined.[6-8,11] We have, however, recently observed tridentate coordination by D-Pen, L-Pen, and L-Cys in complexes of Co(III) and Cr(III).[17,40-42] The geometry of the D-Pen^{2-} ligand appears normal. The bond lengths and angles in the complex are listed in Table III. The dihedral angles associated with the ligands are listed in Table IV.

As can be seen in Figure 2 and in Table III, there is extensive intermolecular hydrogen bonding in the crystals. The amino group of the L-His residue participates in hydrogen bonds of lengths 2.902 (5) and 3.051 (6) Å with the free carboxyl oxygen atom [O(4)] of the D-Pen ligand and with the water molecule. The protonated, uncoordinated imidazole nitrogen atom [N(3)] forms a hydrogen bond of length 2.782 (5) Å to the coordinated histidine oxygen atom O(1). The water molecule, in addition to the acceptor hydrogen bond above, forms hydrogen bonds to the two free carboxyl oxygen atoms O(2) and O(4), with lengths of 2.806 (5) and 2.791 (5) Å, respectively.

It is noteworthy that, in the absence of added oxidant, D-penicillamine evidently oxidizes cobalt(II) to cobalt(III) upon coordination. Thus, in the absence of added penicillamine, the cobalt(II) complex $[\mathrm{Co}(\text{L-His})_2]$ is obtained from the reaction mixture. This oxidizing power of penicillamine is apparently not found in other cysteine analogues; thus, while we have been able to form the title complex and[42] $[\mathrm{Co}(\text{D-Pen})(\text{L-Pen})]^-$ we have failed to obtain their cysteine analogues, and in order to obtain the cobalt(III) complex $[\mathrm{Co}(\mathrm{SMC})_2]^+$, Hidaka and Shimura added a chemical oxidant.[43] In fact, cysteine appears to reduce cobalt(III) to cobalt(II).[41]

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Supplementary Material Available: a listing of observed and calculated structure amplitudes (13 pages). Ordering information is given on any current masthead page.

Table III. Bond Distances (Å) and Bond Angles (deg) with Estimated Standard Deviations

Co-S	2.228 (1)	Co-N(1)	1.933 (3)
Co-O(1)	1.989 (3)	Co-N(2)	1.925 (3)
Co-O(3)	1.921 (3)	Co-N(4)	1.973 (4)
N(1)-C(1)	1.487 (5)	C(6)-N(2)	1.326 (5)
C(1)-C(2)	1.525 (6)	N(4)-C(8)	1.482 (6)
C(1)-C(3)	1.528 (6)	C(8)-C(9)	1.552 (9)
C(3)-O(1)	1.290 (5)	C(9)-C(10)	1.524 (9)
C(3)-O(2)	1.225 (5)	C(9)-C(11)	1.527 (9)
C(2)-C(4)	1.490 (6)	C(9)-S	1.838 (5)
C(4)-C(5)	1.354 (6)	C(8)-C(7)	1.526 (5)
C(4)-N(2)	1.390 (5)	C(7)-O(3)	1.285 (5)
C(5)-N(3)	1.382 (7)	C(7)-O(4)	1.222 (5)
N(3)-C(6)	1.344 (6)		
S-Co-N(1)	94.2 (1)	N(1)-Co-N(4)	98.3 (2)
S-Co-N(2)	92.5 (1)	N(2)-Co-O(1)	92.0 (1)
S-Co-O(1)	174.7 (2)	N(2)-Co-O(3)	91.2 (1)
S-Co-O(3)	92.6 (1)	N(2)-Co-N(4)	173.1 (1)
S-Co-N(4)	85.0 (1)	O(1)-Co-O(3)	90.2 (1)
N(1)-Co-N(2)	88.3 (1)	O(1)-Co-N(4)	90.9 (2)
N(1)-Co-O(1)	83.1 (1)	O(3)-Co-N(4)	82.6 (1)
N(1)-Co-O(3)	173.2 (2)		
Co-N(1)-C(1)	106.4 (2)	C(2)-C(4)-C(5)	127.9 (4)
C(2)-C(1)-C(3)	109.5 (3)	N(2)-C(4)-C(5)	109.4 (4)
N(1)-C(1)-C(2)	110.4 (3)	C(4)-C(5)-N(3)	106.0 (4)
N(1)-C(1)-C(3)	109.2 (3)	C(5)-N(3)-C(6)	108.0 (4)
C(1)-C(2)-C(4)	113.5 (3)	N(3)-C(6)-N(2)	110.6 (4)
C(1)-C(3)-O(1)	114.6 (3)	C(6)-N(2)-C(4)	106.0 (3)
C(1)-C(3)-O(2)	120.1 (4)	C(6)-N(2)-Co	125.8 (3)
O(1)-C(3)-O(2)	125.3 (4)	C(4)-N(2)-Co	128.1 (3)
C(2)-C(4)-N(2)	122.7 (3)		
Co-N(4)-C(8)	101.4 (2)	S-C(9)-C(11)	109.0 (4)
N(4)-C(8)-C(9)	108.7 (3)	C(8)-C(9)-C(10)	109.6 (5)
N(4)-C(8)-C(7)	104.8 (3)	C(8)-C(9)-C(11)	111.4 (4)
C(7)-C(8)-C(9)	110.3 (3)	C(9)-S-Co	97.8 (2)
C(10)-C(9)-C(11)	109.8 (7)	C(8)-C(7)-O(3)	114.0 (3)
S-C(9)-C(8)	106.9 (3)	C(8)-C(7)-O(4)	122.1 (4)
S-C(9)-C(10)	110.1 (5)	O(3)-C(7)-O(4)	123.8 (4)

Hydrogen Bonding

A-B . . C[a]	A . . C	B . . C	A-B-C
N(1)-H(1) . . W^{I}	3.051 (6)	2.36 (6)	172 (5)
N(1)-H(2) . . $\mathrm{O}(4)^{\mathrm{II}}$	2.902 (5)	1.95 (6)	177 (5)
N(3)-H(7) . . $\mathrm{O}(1)^{\mathrm{III}}$	2.782 (5)	2.03 (6)	143 (4)
W-H(18) . . $\mathrm{O}(4)^{\mathrm{II}}$	2.791 (5)	2.10 (8)	154 (9)
W-H(19) . . $\mathrm{O}(2)^{\mathrm{IV}}$	2.806 (5)	1.82 (7)	164 (6)

[a] Roman superscripts refer to atoms in the following positions: I, $1 - x, \frac{1}{2} + y, -z$; II, $1 + x, y, z$; III, $-x, \frac{1}{2} + y, 1 - z$; IV, $x, y, -1 + z$.

Table IV. Dihedral Angles (deg) of Interest for Co(L-His)(D-Pen)

L-Histidine	
$\mathrm{O}(1)\text{-}\mathrm{C}(3)\text{-}\mathrm{C}(1)^{\alpha}\text{-}\mathrm{C}(2)$	101.4[a]
$\mathrm{O}(1)\text{-}\mathrm{C}(3)\text{-}\mathrm{C}(1)^{\alpha}\text{-}\mathrm{N}(1)$	−19.6
$\mathrm{N}(1)\text{-}\mathrm{C}(1)^{\alpha}\text{-}\mathrm{C}(2)\text{-}\mathrm{C}(4)$	54.2
$\mathrm{C}(3)\text{-}\mathrm{C}(1)^{\alpha}\text{-}\mathrm{C}(2)\text{-}\mathrm{C}(4)$	−66.0
$\mathrm{Co}\text{-}\mathrm{N}(1)\text{-}\mathrm{C}(1)^{\alpha}\text{-}\mathrm{C}(3)$	36.4
$\mathrm{Co}\text{-}\mathrm{N}(1)\text{-}\mathrm{C}(1)^{\alpha}\text{-}\mathrm{C}(2)$	−84.0
$\mathrm{Co}\text{-}\mathrm{O}(1)\text{-}\mathrm{C}(3)\text{-}\mathrm{C}(1)^{\alpha}$	−7.2
Co-N(2)-C(4)-C(2)	4.8
$\mathrm{C}(1)^{\alpha}\text{-}\mathrm{C}(2)\text{-}\mathrm{C}(4)\text{-}\mathrm{N}(2)$	−12.5
D-Penicillamine	
$\mathrm{O}(3)\text{-}\mathrm{C}(7)\text{-}\mathrm{C}(8)^{\alpha}\text{-}\mathrm{C}(9)$	−81.0
$\mathrm{O}(3)\text{-}\mathrm{C}(7)\text{-}\mathrm{C}(8)^{\alpha}\text{-}\mathrm{N}(4)$	35.8
$\mathrm{N}(4)\text{-}\mathrm{C}(8)^{\alpha}\text{-}\mathrm{C}(9)\text{-}\mathrm{S}$	−44.4
$\mathrm{Co}\text{-}\mathrm{N}(4)\text{-}\mathrm{C}(8)^{\alpha}\text{-}\mathrm{C}(9)$	68.8
$\mathrm{Co}\text{-}\mathrm{N}(4)\text{-}\mathrm{C}(8)^{\alpha}\text{-}\mathrm{C}(7)$	−49.1
$\mathrm{Co}\text{-}\mathrm{O}(3)\text{-}\mathrm{C}(7)\text{-}\mathrm{C}(8)^{\alpha}$	−2.0
Co-S-C(9)-C(8)	2.8

[a] Values taken as positive when far atom rotates counterclockwise relative to near atom to be eclipsed.

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