Heteroatom Chemistry
Volume 16, Number 4, 2005

Interaction of Pyridine-2,5-dicarboxylic Acid with Heavy Metal Ions in Aqueous Solutions

Eugenijus Norkus,[1] Ernestas Gaidamauskas,[2] Irena Stalnionienė,[1]
and Debbie C. Crans[3]

[1]*Laboratory of Catalysis, Institute of Chemistry, A. Goštauto 9, LT-01108 Vilnius, Lithuania*

[2]*Faculty of Chemistry, Vilnius University, Naugarduko 24, LT-03225 Vilnius, Lithuania*

[3]*Department of Chemistry, Colorado State University, Fort Collins, CO 80523-1872, USA*

Received 16 February 2005; revised 28 February 2005

ABSTRACT: *Interactions between pyridine-2,5-dicarboxylic acid and Zn(II), Ni(II), Pb(II), Cd(II), and Cu(II) were characterized in aqueous solutions (20°C; $I = 0.4$ (KNO_3)) by means of d.c.-polarography, spectrophotometry, and ^1H NMR spectroscopy. Polarography was used to determine the concentration of free metal ions in the presence of 10-fold excess ligand in weakly alkaline solutions, and to determine stability constants for the Zn(II), Cd(II), and Cu(II) complexes with pyridine-2,5-dicarboxylic acid. ^1H NMR spectroscopy was used to further characterize complex formation.*

Heteroatom Chem 16:285–291, 2005;

DOI 10.1002/hc.20123

INTRODUCTION

The interaction of transition and heavy metal ions with naturally occurring ligands in living organisms is important to evaluate potential beneficial and deleterious effects of these ions. Isocinchomeronic acid (pyridine-2,5-dicarboxylic acid, H_2pdca) is an isomer of the naturally occurring pyridine-2,6-dicarboxylic acid. Most studies have focused on the syntheses and structural investigations of metal pdca^{2-} complexes in the solid state. Cu(II) [1], Fe(II) [2], Zn(II) [2–4], Co(II) [5,6], Ag(I) [7], Mn(II), Co(II) [2,5,6], and Ni(II) complexes [2, 6] with pdca^{2-} have been synthesized and characterized. The 1:1 stoichiometry was found in complexes with Cu(II) [1], Ni(II), and Co(II) [6]; the 1:2 stoichiometry was found in complexes with Mn(II) [2], Co(II) [2,5], Ni(II) [2], Fe(II) [2], and Zn(II) [2,4]. A dinuclear complex with the pdca^{2-} anion was observed for Ag(I) [7] and a tetranuclear complex for Zn(II) [3]. Monoanionic Hpdca$^-$ forms complexes with Fe(II), Mn(II), Zn(II), and Co(II) [2,4,5], and dianionic pdca^{2-} forms complexes with Cu(II), Zn(II), and Ag(I) [1,3,7]. In addition, heteronuclear polymeric complexes of Cu(II) and Gd(III) with pdca^{2-} have been prepared [8].

The information on the aqueous speciation of metal ion complexes with pdca^{2-} is limited to Fe, Al, and Cu chemistry. The interaction of Fe(II) and Fe(III) with Hpdca$^-$/pdca^{2-} was characterized [9,10], and Fe in both oxidation states forms 1:1, 1:2, and 1:3 complexes. The log β values are 5.9, 9.3, and 10.6 and 7.8, 13.2, and 23.3, respectively, for Fe(II) and Fe(III) 1:1, 1:2, and 1:3 complexes [10]. Less stable Al(III) complexes with pdca^{2-} (log $\beta_1 = 4.0$ and log $\beta_2 = 7.2$) were also reported [11]. Cu(II) complex formation with pdca^{2-} was investigated in a wide pH range using polarography, spectrophotometry,

---

Correspondence to: Eugenijus Norkus; e-mail: Norkus@ktl.mii.lt.

Contract grant sponsor: The Ministry of Education and Science of Republic of Lithuania.
Contract grant sponsor: Lithuanian State Science and Studies Foundation (project C-03047).
Contract grant sponsor: The National Institutes of Health.

and potentiometric titration [12]. Two classes of Cu(II) species form with pdca^{2-}, $[\text{Cu(pdca)}_2]^{2-}$, and $[\text{Cu(pdca)(OH)}]^{-}$, with log β values of 14.3 and 16.7, respectively [12]. Although the investigations were carried out at high alkali concentrations (up to pH 14), the formation of the soluble Cu(II) hydroxy-complex Cu(OH)_4^{2-} with log $\beta_4 = 15.5$ [13] was not discussed [12].

The UV-visible, IR absorption, and ^{13}C NMR spectra of pyridine-2,5-dicarboxylic acid and of the other isomers of pyridinedicarboxylic acid were determined [14]. The pK_a values for H_2pdca have previously been reported [10–12]; the pK_{a1} values were 2.35 [10], 2.17 [11], and 2.35 [12], and the pK_{a2} values were 4.96 [10], 4.58 [11], and 4.63 [12]. This information documents that in neutral and alkaline solutions the ligand exists as dianionic pdca^{2-}.

Given the recent results showing that some transition metal complexes with the 2,6-dipicolinic acid have beneficial effects in normalizing elevated blood glucose levels in STZ-induced diabetic rats [15,16], fundamental information on the solution chemistry of metal complexes with dipicolinic acid isomers is important. The present study was carried out to investigate equilibria in solutions of H_2pdca in the presence of the divalent metal ions Zn(II), Ni(II), Pb(II), Cd(II), and Cu(II) over a wide pH range.

RESULTS AND DISCUSSION

The cathodic waves of H_2pdca reduction were determined at pH values ranging from 1.5 to 8.0 to investigate the electrochemical behavior of H_2pdca on a dropping mercury electrode. With an increase in solution pH the half-wave potential ($E_{1/2}$) of ligand reduction shifts to more negative potentials with a simultaneous decrease in the limiting current value. These results might indicate the irreversible two-electron reduction of the protonated forms H_2pdca/Hpdca^{-} ($E_{1/2}$ shift is ca. −70 to −80 mV pH^{-1}). Only protonated forms of the ligand are involved in the reduction process, since the reduction current completely disappears above pH 8.0. The previously determined pK_{a2} is equal to 4.5–5 [10–12], consistent with the presence of only pdca^{2-} at pH above 8.0. The data obtained by polarography using Zn(II), Cd(II), and Cu(II) are compiled in Table 1.

Zn(II)-H$_2$pdca

The polarographic data obtained in acid solutions for the Zn(II)-H_2pdca system are distorted due to the ligand reduction on a dropping mercury electrode, and their analysis is not possible. In alkaline solutions of pdca^{2-} ($7.0 < \text{pH} < 10.0$), the half-wave potential of Zn(II) reduction does not depend on solution pH and remains constant ($\Delta E^{r}_{1/2} = -0.209$ V, Table 1) due to successive deprotonations of H_2pdca. The $E_{1/2}$ of the quasi-reversible polarographic waves of Zn(II) reduction shifts by ca. −60 mV with a 10-fold increase in ligand concentration, which suggests participation of two pdca^{2-} anions in zinc(II) complex formation. The calculated value of the $[\text{Zn(pdca)}_2]^{2-}$ complex stability constant (log $\beta_2 = 12.0$, Table 1) gives a formation constant for a 1:2 Zn(II) complex of medium stability.

The polarographic experiments are limited in experimental conditions since they require at least 10-fold excess of ligand, and therefore will only determine the predominating $[\text{Zn(pdca)}_2]^{2-}$ complex under conditions of excess ligand. To characterize the complexes further, ^{1}H NMR spectra were recorded. The pyridine-2,5-dicarboxylic at pH 7 yields three signals of equal intensity: (8.94 (H^1), 8.29 (H^2), and 7.93 ppm (H^3)) (Fig. 1g) with three coupling constants ($\mathbf{J}_{(H2,H3)} = 8.1$, $\mathbf{J}_{(H1,H2)} = 2.2$ and $\mathbf{J}_{(H1,H3)} = 1.2$ Hz). These parameters are similar to those reported previously in d_6-DMSO [17], and H^1, H^2 and H^3 protons are readily assigned to the 6-H, 4-H and 3-H protons of the pyridine ring, respectively (Scheme 1).

The addition of Zn(II) ions results in a downfield shift for H^2 and H^3 protons and an upfield shift for the H^1 proton (Fig. 1, spectra f and e) indicating complex formation. Coordination induced shifts (CIS = $\delta_{\text{Complex}} - \delta_{\text{Ligand}}$) at the molar L:M ratio of 2:1 are equal

TABLE 1 Half-Wave Potential Shifts, Predominating Complexes, Stability Constants and Free Metal Ion Concentrations in Solutions of Pyridine-2,5-dicarboxylic Acid and Heavy Metal Ions ($[\text{M(II)}]_0$: 5×10^{-4} mol dm^{-3}, $[H_2\text{pdca}]_0$: 5×10^{-3} mol dm^{-3}; $I = 0.4$ (KNO_3); 20°C)

Metal (II) Ion	*Solution pH*	*$\Delta E^{r}_{1/2}$ (V)*	*Major Species*	*Logarithm of Stability Constant*	*[M(II)] (mol dm^{-3})*
Zn (II)	7.0–10.0	−0.209	$[\text{Zn(pdca)}_2]^{2-}$	12.0	3.3×10^{-11}
Cd (II)	5.0–11.0	−0.062	[Cd(pdca)]	4.5	3.6×10^{-6}
Cu (II)	4.0–11.0	−0.270	$[\text{Cu(pdca)}_2]^{2-}$	14.1	2.6×10^{-13}

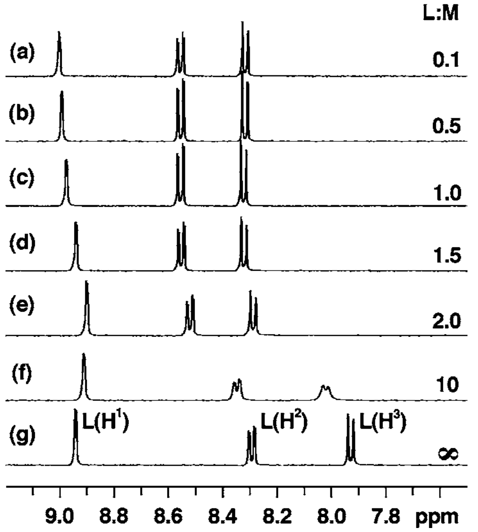
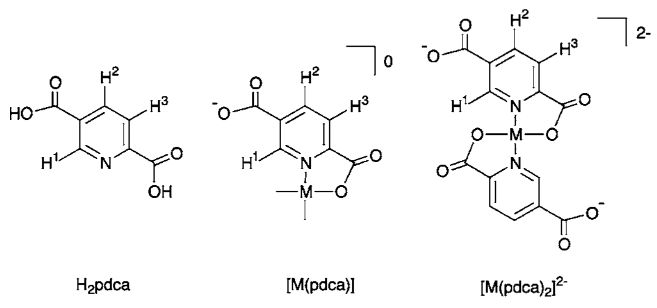


FIGURE 1 ^{1}H NMR spectra of solutions containing 5.0×10^{-3} mol dm^{-3} of pdca^{2-} and (a) 5.0×10^{-2} mol dm^{-3}; (b) 1.0×10^{-2} mol dm^{-3}; (c) 5×10^{-3} mol dm^{-3}; (d) 3.3×10^{-3} mol dm^{-3}; (e) 2.5×10^{-3} mol dm^{-3}; (f) 5.0×10^{-4} mol dm^{-3}, and (g) 0 mol dm^{-3} of $ZnSO_4$ at pH 7.4 ± 0.4. Ligand to metal ratios (L:M) are indicated. Proton numbering in the free ligand (L) is shown in Scheme 1.

to −0.04 (H^1), 0.23 (H^2), and 0.36 (H^3) ppm. At a L:M ratio of 10:1 only three sets of signals are observed. Since these solutions contain some free ligand and only three sets of signals are observed, which show that the complex and free ligand are in fast exchange. Upon an increase in the Zn(II) concentration (i.e. a decrease in L:M ratio), all signals shift further downfield (Fig. 1, spectra e–a), and CIS at the molar L:M ratio 10:1 have increased slightly to 0.1 (H^1), 0.26 (H^2), and 0.38 (H^3) ppm.

Based on the combined polarographic and NMR studies, we conclude that for the Zn-H_2pdca system the most stable complex is a 1:2 species ($[Zn(pdca)_2]^{2-}$), and the 1:1 complex is significantly less stable.



SCHEME 1 Schematic drawing of the structures of pyridine-2,5-dicarboxylic acid (H_2pdca) and the divalent metal complexes [M(pdca)] and $[M(pdca)_2]^{2-}$.

Ni(II)-H$_2$pdca

The polarographic waves of Ni(II) reduction in H_2pdca containing solutions are irreversible. The height of these waves is much higher compared to those of typical diffusion-controlled, two-electron reduction waves. This suggests that the waves are of a catalytic nature, and that either the Ni(II) ions or a complex catalyses the process of H^+ ion reduction on a dropping mercury electrode. Since studies in which Ni(II) ions alone did not show these waves of higher current, we conclude that a Ni(II) complex is the cause of this effect. The spectrophotometric investigations carried out in weakly acidic and alkaline solutions ($5.0 < pH < 12.0$) showed 1:2 Ni(II)-pdca^{2-} complex formation under conditions of ligand excess. The absorption maximum of this compound is at $\lambda = 585$ nm with a molar extinction coefficient of 13 dm^3 mol^{-1} cm^{-1} (Fig. 2, curve 4). A comparison of the spectral characteristics of uncomplexed Ni(II) ions with those of the Ni(II)-pdca^{2-} complex shows the shift of the absorption maximum from 710 nm to 585 nm with an increase in molar extinction coefficient values from ca. 2 to 13 dm^3 mol^{-1} cm^{-1} (Fig. 2, cf. curves 3 and 4).

The addition of Ni(II) ions to the pdca^{2-} caused the appearance of dramatically shifted resonances at 15.7, 54, and 148 ppm, which were well resolved at low L:M ratio (Fig. 3d). The ^{1}H NMR signals were assigned as H^2 (15.7 ppm), H^3 (54 ppm), and H^1 (148 ppm). The very broad ^{1}H signal at 148 ppm was assigned to H^1 based on known shift patterns of

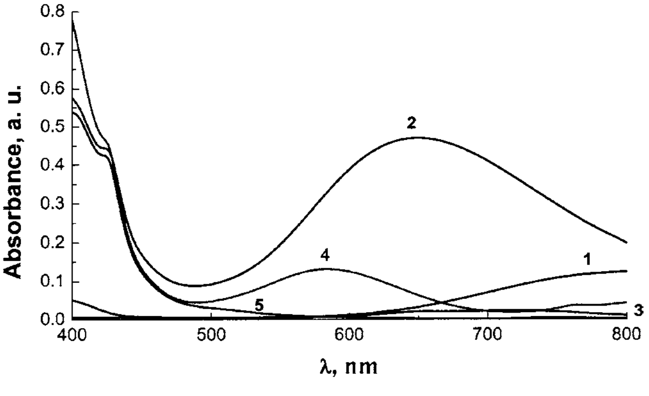


FIGURE 2 Visible absorption spectra for Cu(II) and Ni(II) solutions in the presence or absence of pyridine-2,5-dicarboxylic acid. The solutions contain: (1) 1.0×10^{-2} mol dm^{-3} $Cu(NO_3)_2$, pH 4.0; (2) 1.0×10^{-2} mol dm^{-3} $Cu(NO_3)_2$, 5.0×10^{-2} mol dm^{-3} pdca^{2-}, pH 8.0; (3) 1.0×10^{-2} mol dm^{-3} $Ni(NO_3)_2$, pH 4.0; (4) 1.0×10^{-2} mol dm^{-3} $Ni(NO_3)_2$, 5.0×10^{-2} mol dm^{-3} pdca^{2-}, pH 8.0; (5) 5.0×10^{-2} mol dm^{-3} pdca^{2-}, pH 8.0. $I = 0.4$ (KNO_3); 20°C. The spectra were recorded using 1.0 cm path length quartz cells with water as the blank solution.

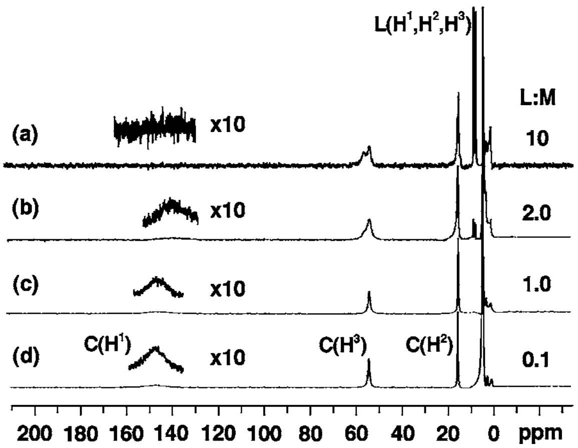


FIGURE 3 Paramagnetic ^{1}H NMR spectra of solutions containing 5.0×10^{-3} mol dm^{-3} of pdca^{2-} and (a) 5.0×10^{-4} mol dm^{-3}; (b) 2.5×10^{-3} mol dm^{-3}; (c) 5.0×10^{-3} mol dm^{-3} and (d) 5×10^{-2} mol dm^{-3} of NiSO$_4$ at pH 7.4 ± 0.3. Ligand to metal ratios (L:M) are indicated. Proton numbering in the complex [M(pdca)] is shown in Scheme 1.

pyridine-containing paramagnetic metal complexes [18]. The signal's broadness and large shift reflect the direct spin delocalization throughout the molecule [19]. Since H^3 is four bonds from the metal ion and H^2 is five bonds from the metal, we assign the signal at 54 ppm to H^3 and that at 15.7 ppm to H^2. The same spectra were observed at L:M ratios of 1 to 0.1 (Fig. 3c and d), however, when the ratio increased to 2, the signal at 54 ppm was a major signal with a small shoulder at 57 ppm (Fig. 3b). In this spectrum, signals at 7.97, 8.32, and 8.97 ppm were also observed, which indicate the presence of free ligand, and demonstrate that the complexes in the Ni-pdca^{2-} system are in slow exchange with free ligand. Furthermore, the two signals in the range 54–57 ppm indicate that two different complexes exist in solution. Indeed, the signal at 15.7 ppm also shows a splitting. These observations are confirmed in a spectrum obtained at L:M ratio of 10:1 (Fig. 3a). We assign the signals observed at low L:M ratios to a 1:1 complex and the signal at higher resonance at high L:M ratios to a 1:2 complex. We conclude that both 1:1 and 1:2 complexes form in aqueous solution and that they are in slow exchange with free ligand.

Pb(II)-H$_2$pdca

The $E_{1/2}$ values of Pb(II) reduction did not change from pH 1.5 to 2.7. Since the values were similar to those of free Pb(II), no complexation seems to take place at low pH values. Increasing the solution pH up to 11.0 resulted in precipitates at various pH values. In the acidic to neutral pH range, the precipitating compound could be a Pb(II) complex with Hpdca$^-$. In alkaline solutions the precipitation of insoluble Pb(OH)$_2$ is likely. No precipitate is formed at pH above 12.0, but at that pH the polarographic measurements showed no evidence for a soluble Pb(II) complex with pdca^{2-}. The dissolution of the Pb(OH)$_2$ precipitate at pH > 12 can be attributed to the formation of a soluble Pb(II) hydroxy-complex, e.g. Pb(OH)$_3^-$ [20]. This system was not investigated further.

Cd(II)-H$_2$pdca

The Cd(II)-H$_2$pdca system differs from that of the Pb(II)-H$_2$pdca system in that soluble complexes are formed in the pH region from 2.0 to 11.0. Upon increasing the pH from 2.0 to 6.0, the half-wave potential of Cd(II) reduction in the presence of the ligand shifts to more negative potentials. A further pH increase does not change the value of $E_{1/2}$ ($\Delta E^{r}_{1/2} = -0.062$ V, Table 1) indicating formation of a complex. The polarographic data are in accordance with the formation of a 1:1 Cd(II)-H$_2$pdca complex. Since the calculated logarithm of the stability constant is 4.5, this complex is categorized as a weak complex. No 1:2 complex formation was observed in polarographic experiments even in the presence of 100-fold ligand excess.

The addition of Cd(II) ions results in a downfield shift for the H^2 and H^3 protons and an upfield chemical shift for H^1 (Fig. 4, spectra (f) and (e)) indicating

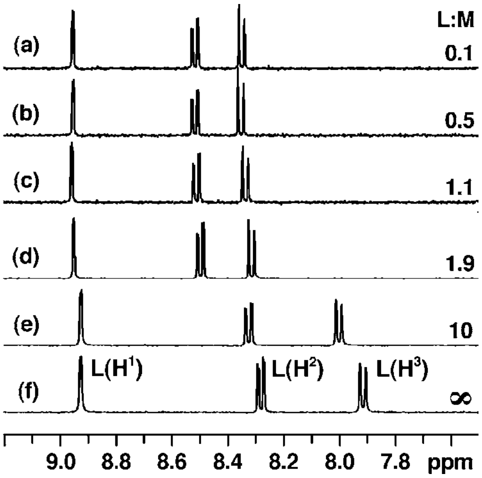


FIGURE 4 ^{1}H NMR spectra of solutions containing 5.0×10^{-3} mol dm^{-3} of pdca^{2-} and (a) 5.0×10^{-2} mol dm^{-3}; (b) 1.0×10^{-2} mol dm^{-3}; (c) 4.5×10^{-3} mol dm^{-3}; (d) 2.6×10^{-3} mol dm^{-3}; (e) 5×10^{-4} mol dm^{-3} and (f) 0 mol dm^{-3} of CdSO$_4$ at pH 7.4 ± 0.3. Ligand to metal ratios (L:M) are indicated. Proton numbering in the free ligand (L) is shown in Scheme 1.

complex formation. The CIS values at the molar M:L ratio 1.9:1 are 0.03 (H^1), 0.22 (H^2), and 0.39 (H^3) ppm. These are values similar to those obtained with the Zn(II) metal ion. A further increase in the Cd(II) concentration (low L:M ratios, Fig. 4, spectra (c)–(a)) does not change the position of any of the signals, suggesting that the same complex remains in solutions with L:M ratios from 0.1 to 1.9. Based on results obtained by polarography, we conclude that this is a 1:1 complex, contrary to the Zn(II)-H_2pdca. Similar to the Zn(II) complex, only three resonances were observed at all L:M ratios, supporting the interpretation that Cd(II) complexes are in fast exchange with free ligand.

Cu(II)-H_2pdca

When investigating the equilibria in Cu(II) solutions containing pyridine-2,5-dicarboxylic acid, it was found that an insoluble complex is formed in an acidic medium at $pH < 4$ (as in case of Pb(II)-H_2pdca). A further increase in solution pH leads to dissolution of the precipitate. The quasi-reversible polarographic waves of Cu(II) reduction with a near constant value of the half-wave potential ($\Delta E^{r}_{1/2} = -0.270$ V, Table 1) are observed in these solutions. The $E_{1/2}$ of the quasi-reversible polarographic waves of Cu(II) reduction shifts by ca. −60 mV with a 10-fold increase in ligand concentration suggesting participation of two $pdca^{2-}$ anions in complex formation. The calculated value of the $[Cu(pdca)_2]^{2-}$ complex stability constant is comparatively high ($\log \beta_2 = 14.1$). The Cu(II) ion forms the most stable complex with the ligand of all the metal ions investigated in this work. The absorption maximum of this complex is at $\lambda = 650$ nm with a molar extinction coefficient being 47 $dm^3\ mol^{-1}\ cm^{-1}$ (Fig. 3, curve 2). A comparison of the spectral characteristics of uncomplexed Cu(II) ions with those of the $[Cu(pdca)_2]^{2-}$ complex shows a shift of the absorption maximum to shorter wavelengths from 800 nm to 650 nm and an increase of the molar extinction coefficient values from 11 to 47 $dm^3\ mol^{-1}\ cm^{-1}$ (Fig. 2, cf. curves 1 and 2).

No shift of the $E_{1/2}$ for Cu(II) reduction in alkaline solutions of $H_2pdca/Hpdca^-/pdca^{2-}$ was observed in the solutions investigated (up to pH 13.0), showing that no additional complex forms. Therefore, our results do not support the observations of $[Cu(pdca)(OH)]^-$ as was described previously [12]. An alternative explanation for these observations is that the $[Cu(pdca)_2]^{2-}$ complex decomposes and converts to $[Cu(OH)_4]^{2-}$ at $pH > 13$ [12]. Such processes for Cu(II) complexes are well known [13,21,22].

The fast Cu(II) relaxation that leads to very broad ^1H NMR resonances [23] limits the use of ^1H NMR spectra for the characterization of this system and was not attempted.

Diffusion Coefficients and Free Metal Ion Concentration

The diffusion coefficients of Zn(II), Cd(II), and Cu(II) complexes with the pyridine-2,5-dicarboxylic acid in 0.4 M KNO_3 solution were calculated from polarographic data according to [29]. The diffusion coefficient values are listed in Table 2. The results obtained are in good agreement with the expected size of the complex species, i.e. the highest value of the diffusion coefficient was obtained for the Cd(II) complex, followed by the Cu(II) and Zn(II) complexes. The Cd(II) complex contains only one ligand molecule and is thus neutrally charged; however, the Cu(II) and Zn(II) complexes each contain two ligand molecules and have an overall dianioinic charge.

By knowing the total metal ion concentration and observing the shift of the reversible half-wave potential of metal ion reduction ($\Delta E^{r}_{1/2}$) in solution, polarography allows the determination of free (uncomplexed) metal ion concentration in the presence of different complexing agents [21,22,24–27]. These types of results are of particular interest given the recent reports that free metal ions in biology are not as common as previously anticipated [28]. The results obtained for Zn(II), Cd(II), and Cu(II) in solutions with total metal ion concentrations of 5×10^{-4} mol dm^{-3} and 10-fold excess of H_2pdca show a decrease in free metal ion concentrations from ca. 10^{-6} mol dm^3 to ca. 10^{-13} mol dm^{-3} (Table 1). Thus, a 10-fold excess of the ligand (at 5×10^{-3} mol dm^{-3}) reduces the concentration of free metal ions in weakly acid-alkaline solutions ca. 9 orders in magnitude for Cu(II), ca. 7 orders in magnitude for Zn(II), and ca. 2 orders in magnitude for Cd(II). These data show that even a relatively weak ligand such as $dipic^{2-}$ has a profound effect on free metal ion concentration consisting with the recent report suggesting that free metal ions do not exist in biological fluids.

TABLE 2 Diffusion Coefficient Values of Metal(II) Ion Complexes with Pyridine-2,5-dicarboxylic Acid at 20°C and $I = 0.4$ (KNO_3)

Complex	*Solution pH*	*Diffusion Coefficient ($cm^2\ s^{-1}$)*
$[Zn(pdca)_2]^{2-}$	7.0–10.0	4.4×10^{-6}
$[Cd(pdca)]$	5.0–11.0	7.8×10^{-6}
$[Cu(pdca)_2]^{2-}$	4.0–11.0	7.2×10^{-6}

EXPERIMENTAL

Reagents

The pyridine-2,5-dicarboxylic acid (H_2pdca) was obtained from Aldrich in 98% purity. Unless otherwise specified analytical grade reagents were used. KNO_3 and KOH solutions were used to keep the ionic strength (I) of the solutions constant and equal in polarographic and spectrophotometric experiments (0.4 mol dm^{-3}). The solutions for polarography and spectrophotometry were prepared in triply distilled water.

Stock solutions of 0.1 mol dm^{-3} of $CdSO_4$, $ZnSO_4$, $NiCl_2$, $CuSO_4$, and of 0.05 mol dm^{-3} of pyridine-2,5-dicarboxylic acid (H_2pdca) were prepared by dissolving the solids in D_2O for NMR experiments. The solid ligand completely dissolved upon addition of NaOD solution (pH 5). Solutions containing 5×10^{-3} mol dm^{-3} of pdca^{2-} and 0, 5×10^{-4}, 2.5×10^{-3}, 3.3×10^{-3}, 5.0×10^{-3}, 1.0×10^{-2}, and 5.0×10^{-2} mol dm^{-3} of metal ions were prepared, and the solution pH values were adjusted to 7.4 ± 0.3 just before the spectra were recorded. Insoluble hydroxides formed in some cases with Cd(II) and Cu(II) salts, and were removed by centrifugation. The supernant solutions were used to acquire spectra. The pH readings were taken with an Orion 420 A + pH-meter equipped with a Corning semi-micro combo glass electrode calibrated with aqueous pH 7.00 and pH 4.00 buffers. No corrections were made for pH values measured in the presence of deuterated solvent.

Apparatus

The polarographic curves were recorded by a *PU-1* polarograph using a dropping mercury electrode in a thermostated three-electrode cell at 20 ± 0.1°C. The potential scanning rate was 100 mV min^{-1}. The capillary characteristics were $m = 2.95 \times 10^{-3}$ g s^{-1}, $t = 3.73$ s. The reference electrode was a Ag/AgCl electrode filled with saturated KCl solution. The solutions were purged with Ar before acquiring data. The visible spectra were recorded with a Perkin Elmer Lambda 35 UV/VIS spectrometer at 20 ± 1°C in 1.0 cm path length quartz cells. The optical blank solution was triply distilled water. ^{1}H NMR spectra of diamagnetic species were recorded on a Varian Unity-400 spectrometer using standard acquisition parameters. Paramagnetic ^{1}H spectra were acquired on Varian Inova-300 spectrometer operating at ambient temperature (22 ± 1°C), using a standard solvent presaturation pulse sequence with no relaxation delay, a 0.1 s saturation delay, a 65° flip angle, and a 0.09 s acquisition time. The 120 kHz spectral window contained 21 kB data points, and 1024 scans were sufficient to obtain a good signal to noise ratio. An exponential line broadening of 20 Hz was applied before the processing of each spectrum. Chemical shifts were referenced versus the residual solvent peak for paramagnetic spectra, and versus an external sample of DSS for diamagnetic spectra.

Procedures

The procedures of analysis of polarographic data, determination of stability constants, and concentration of free (uncomplexed) metal ions, calculation of diffusion coefficients have been described in [29] and elsewhere [30,31].

CONCLUSIONS

In solutions of excess ligand Zn(II), Ni(II) and Cu(II) form 1:2 complexes with the dianion pdca^{2-} in weakly acidic-alkaline solutions. The values of log β_2 for Zn(II) and Cu(II) complexes are 12.0 and 14.1, respectively. The formation of a 1:1 complex was observed for Cd(II) (log $\beta_1 = 4.5$). The values of the diffusion coefficients of complexes investigated are equal to 7.8×10^{-6}, 7.2×10^{-6}, and 4.4×10^{-6} cm^2 s^{-1} for [Cd(pdca)], [Cu(pdca)$_2$]$^{2-}$, and [Zn(pdca)$_2$]$^{2-}$, respectively; these values reflect the size and charge of the complexes. A 10-fold excess of H_2pdca reduces the concentration of free Cu(II), Zn(II), and Cd(II) ions from 2 to 9 orders in magnitude, depending on the stability constant of the complex formed. This information supports the recent studies suggesting that exceedingly low levels of metal ions are actually free in biological systems.

REFERENCES

[1] Min, D. W.; Yoon, S. S.; Jung, D. Y.; Lee, C. Y.; Kim, Y.; Han, W. S.; Lee, S. W. Inorg Chim Acta 2001, 324, 293.
[2] Goher, M. A. S.; Mak, T. C. W. Struct Chem 1994, 5, 165.
[3] Liang, Y. C.; Hong, M. C.; Cao, R. Acta Crystallogr, Sect E 2001, 57, M145.
[4] Xu, H. T.; Zheng, N. W.; Xu, H. H.; Wu, Y. G.; Yang, R. Y.; Ye, E. Y.; Jin, X. L. J Molec Struct 2001, 597, 1.
[5] Liang, Y. C.; Cao, R.; Hong, M. C.; Shi, Q.; Sun, D. F.; Weng, J. B. Acta Crystallogr, Sect 2001, 57, M382.
[6] Plater, M. J.; Foreman, M. R. S.; Howie, R. A.; Lachowski, E. E. J Chem. Res, Synop 1998, 754.
[7] Brzyska, W.; Ozga, W. Polish J Chem 1997, 71, 436.
[8] Liang, Y.; Cao, R.; Su, W.; Hong, M.; Zhang, W. Angew Chem, Int Ed 2000, 39, 3304.
[9] Marimoto, I.; Sato, T. Bull Chem Soc Japan 1963, 36, 605.
[10] Ooi, G. K. S.; Magee, J. J Inorg Nucl Chem 1970, 32, 3315.
[11] Napoli, A. J Inorg Nucl Chem 1970, 32, 1907.

[12] Petitfaux, C.; Fournaise, R. Bull Soc Chim France 1972, 915.
[13] Norkus, E.; Vaškelis, A. Polyhedron 1994, 13, 3041.
[14] Wasylina, L.; Kucharska, E.; Weglinski, Z.; Puszko, A. Khim Geterotsikl Soed 1999, 210.
[15] Crans, D. C. J Inorg Biochem 2000, 80, 123.
[16] Yang, L.; Crans, D. C.; Miller, S. M.; la Cour, A.; Anderson, O. P.; Kaszynski, P. M.; Godzala, M. E.; Austin, L. D.; Willsky, G. R. Inorg Chem 2002, 41, 4859.
[17] SDBSWeb: http://www.aist.go.jp/RIODB/SDBS/, SDBS No. 2997; access date: July 24th, 2002.
[18] Zang, Y.; Jang, H. G.; Chiou, Y.-M.; Hendrich, M. P.; Que, L. Inorg Chim Acta 1993, 213, 41.
[19] Ming, L.-J. in: Que, L. (Ed.) Physical Methods in Bioinorganic Chemistry; University Science Books: Sausalito, 2000, pp. 375–464.
[20] Norkus, E.; Grincienė, G.; Vaitkus, R. Carbohydr Res 2002, 337, 1657.
[21] Norkus, E.; Vaškelis, A.; Žakaitė, I. Talanta 1996, 43, 465.
[22] Norkus, E.; Vaičiūnienė, J.; Vuorinen, T.; Heikkilä, M. Carbohydr Polym 2002, 50, 159.
[23] Bertini, I.; Dei, A.; Scozzafava, A. Inorg Chem 1975, 14, 1526.
[24] Norkus, E.; Vaškelis, A.; Žakaitė, I.; Reklaitis, J. Talanta 1995, 42, 1701.
[25] Norkus, E.; Vaičiūnienė, J.; Vuorinen, T.; Macalady, D. L. Carbohydr Polym 2004, 55, 47.
[26] Norkus, E.; Pauliukaitė, R. Polish J Chem 2000, 74, 1231.
[27] Norkus, E.; Vaičiūnienė, J.; Vuorinen, T.; Gaidamauskas, E.; Reklaitis, J.; Jääskeläinen, A.-S.; Crans, D. C. Carbohydr Res 2004, 339, 599.
[28] Rae, T. D.; Schmidt, P. J.; Pufahl, R. A.; Culotta, V. C.; O'Halloran; T. V. Science 1999, 284, 805.
[29] Norkus, E.; Stalnionienė, I.; Crans, D. C. Heteroatom Chem 2003, 14, 625.
[30] Norkus, E.; Grincienė, G.; Vuorinen, T.; Vaitkus, R.; Butkus, E. Int J Biol Macomol 2003, 33, 251.
[31] Norkus, E.; Grincienė, G.; Vuorinen, T.; Vaitkus, R. J Incl Phenom Macrocycl Chem 2004, 48, 147.