(a) Oligomer (VII) or Dimer $[Pt_2Me_2(\mu\text{-Cl})(\mu\text{-dppm})_2]Cl$ (VIa). An aliquot of a standardized solution of hydrogen chloride in benzene (7.24 mL containing 1.64 mmol of HCl) was slowly added to $[PtMe_2(dppm)]$ (1.00 g, 1.64 mmol) in benzene (30 mL) kept at just above its freezing point. The solution was stirred during the addition (30 min) and then for a further 30 min. During this time an off-white solid formed in the yellow solution and was recovered by filtration to yield the oligomeric form VII of [PtCl(Me)(dppm)] (0.810 g, 78%) [ν(Pt–Cl) 261 cm^{-1}]. The ^1H NMR spectrum showed that it gave the cation $[Pt_2Me_2(\mu\text{-Cl})(\mu\text{-dppm})_2]^+$ in dichloromethane-d_2 solution. A portion of VII (0.373 g) was recrystallized from dichloromethane/hexane to give the dimer $[Pt_2Me_2(\mu\text{-Cl})(\mu\text{-dppm})_2]Cl$ (VIa) in 82% yield.

Six experiments similar to the above were carried out but VII was obtained as described from only three of these. The remainder gave instead fairly pure VIa (~70% yield) as the initial product. As a preparation if VII, the procedure is therefore somewhat unpredictable, but it is an excellent and reliable route to VIa since recrystallization of the initial product, irrespective of whether this is VII or VIa, affords pure VIa. Anal. Calcd for $[Pt_2Me_2(\mu\text{-Cl})(\mu\text{-dppm})_2]Cl$: C, 49.6; H, 4.0; Cl, 5.6; P, 9.8. Found: C, 49.5; H, 4.1; Cl, 5.7; P, 9.9.

(b) The Monomer [PtCl(Me)(dppm)] (IV). A solution of acetyl chloride (0.119 g, 1.52 mmol) in dichloromethane (4.1 mL) was added over ~10 min at 20 °C with stirring to $[PtMe_2(dppm)]$ (0.927 g, 1.52 mmol) dissolved in dichloromethane (5 mL) and methanol (3.5 mL). The solution became somewhat deeper yellow and was then stirred for a further 15 min. The solvent was then mostly removed in a stream of nitrogen to produce a crop of white crystals in a small amount of yellow oily mother liquor. Benzene (~3 mL) was added to this mixture, diluting the mother liquor but not dissolving the crystals. These were recovered by filtration, washed with benzene, and dried, yielding [PtCl(Me)(dppm)] (0.614 g, 0.975 mmol, 64%). The ^1H NMR spectrum showed no trace of impurity. A portion of this product (0.14 g) was recrystallized from dichloromethane/hexane in 80% yield but the recrystallized material had an unchanged IR spectrum. A ν(Pt–Cl) band occurs at 290 cm^{-1} (lit.[4] 292 cm^{-1}). Anal. Calcd for [PtClMe(dppm)]: C, 49.6; H, 4.0; Cl, 5.6; P, 9.8. Found: C, 49.4; H, 3.9; Cl, 5.8; P, 9.9.

Preparation of $[Pt_2Me_2(\mu\text{-Cl})(\mu\text{-dppm})_2][PF_6]$ (VIb). A sample of potassium hexafluorophosphate (0.15 g, 0.81 mmol) was partially dissolved in methanol (5 mL) and the mixture added to the dimer $[Pt_2Me_2(\mu\text{-Cl})(\mu\text{-dppm})_2]Cl$ (VIa) (0.200 g, 0.159 mmol) in dichloromethane (5 mL). The reaction mixture was stirred for ~30 min at room temperature. Hexane was then added to precipitate the crude product together with the potassium salts. The latter were removed by washing the solid with water to leave $[Pt_2Me_2(\mu\text{-Cl})(\mu\text{-dppm})_2][PF_6]$ (0.194 g, 89%). Recrystallization from dichloromethane/hexane gave the pure product (0.145 g, 67% overall yield). Anal. Calcd for $[Pt_2Me_2(\mu\text{-Cl})(\mu\text{-dppm})_2][PF_6]$: C, 45.6; H, 3.7; Cl, 2.6; F, 8.3; P, 11.3. Found: C, 45.5; H, 3.6; Cl, 2.8; F, 8.1; P, 11.3.

Acknowledgment. We thank the SRC for a research studentship (to S.J.C.), the NSERC (Canada) for financial support (to R.J.P.), NATO for a travel grant (to M.P.B. and R.J.P.), Johnson-Matthey Ltd. for the generous loan of platinum, and Bruker Ltd. for the resolution-enhanced 200-MHz NMR spectrum.

Registry No. IV, 76584-41-3; V, 59335-15-8; VIa, 76648-80-1; VIb, 75862-29-2; VII, 76648-81-2; $PtMe_2(dppm)$, 52595-90-1; $PtCl_2(dppm)$, 52595-94-5; methyllithium, 917-54-4; HCl, 7647-01-0.

Contribution from the Department of Chemistry, University of Malaya, Kuala Lumpur, Malaysia

Mixed-Ligand Complexes of Palladium. 5. Diaqua(ethylenediamine)palladium(II) Complexes of Ethanolamine, L-Serine, L-Threonine, L-Homoserine, and L-Hydroxyproline

MENG-CHAY LIM

Received April 3, 1980

The reactions of $[Pd(en)(OH_2)_2]^{2+}$ (en = ethylenediamine) with ethanolamine, L-serine, L-threonine, L-homoserine, and L-hydroxyproline in 0.1 M KNO_3 at 25 °C have been studied by potentiometric titrations. The results obtained can be explained by equilibria i and ii, where L = neutral ethanolamine or the anionic form of the amino acids; charges have been

$$[Pd(en)(OH_2)_2] + L \overset{K_1}{\rightleftharpoons} [Pd(en)L] + 2H_2O \quad \text{(i)}$$

$$[Pd(en)L] \overset{K_1'}{\rightleftharpoons} [Pd(en)(LH_{-1})] + H^+ \quad \text{(ii)}$$

left out for simplification. The values of log K_1 and pK_1' of these complexes suggest that, for ethanolamine, the neutral alcohol group coordinates to palladium, for L-serine, L-threonine, and L-homoserine, the neutral alcohol groups do not coordinate to the metal center, but coordinations occur upon deprotonations of the alcohol groups, and, for L-hydroxyproline, both the neutral alcohol group and the deprotonated alkoxyl group derived therefrom do not coordinate to the metal center.

The β-alcohol group in the side chain of the amino acid serine has been found to play an essential role in the functioning of a number of proteolytic enzymes, e.g., chymotrypsin and subtilisin.[1] It is of interest to investigate the coordinating ability of such alcohol groups to metal ions. As pointed out recently, there appears to be no general agreement regarding the participation of the β-alcohol groups in chelate formation in the metal complexes of serine and threonine.[2] While basicity-adjusted binding strength indicates weak chelation of the groups to hexacoordinate metal ions such as Co^{2+}, Ni^{2+}, and Zn^{2+}, X-ray structural studies in the solid state do not support this conclusion.[2-6] On the other hand it has been reported that in basic solutions Cu^{2+} promotes the ionization of the alcohol hydrogens from its bis complex with threonine with pK's of 10.3 and 11.3.[7]

No stability constants of palladium complexes of serine or threonine have been reported. In connection with our study of the mixed-ligand complexes of palladium with asparagine and glutamine, we have shown that owing to the very high

(1) S. A. Bernhard, "The Structure and Function of Enzymes", W. A. Benjamin, New York, 1968 Chapter 8.
(2) R. Bruce Martin, *Met. Ions Biol. Syst.*, **9**, Chapter 1 (1979).
(3) D. Van der Helm and M. B. Hossain, *Acta Crystallogr., Sect. B*, **B25**, 457 (1969).
(4) D. Van der Helm and W. A. Franks, *Acta Crystallogr., Sect. B*, **B25**, 451 (1969).
(5) D. Van der Helm, A. F. Nicholas, and C. G. Fisher, *Acta Crystallogr., Sect. B*, **B26**, 1172 (1970).
(6) H. C. Freeman, J. M. Guss, M. J. Healy, R.-P. Martin, C. E. Nockolds, and B. Sarkar, *J. Chem. Soc. D*, 225 (1969).
(7) P. Grenouillet, R.-P. Martin, A. Rossi, and M. Ptak, *Biochim. Biophys. Acta*, **322**, 185 (1973).

0020-1669/81/1320-1377$01.25/0

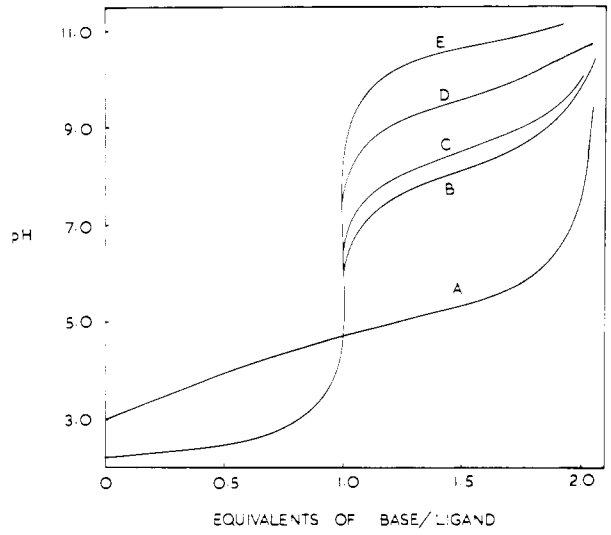

Figure 1. Curves for titration of solutions containing 1:1 mole ratio of $[Pd(en)(OH_2)_2](NO_3)_2$ to ligand against sodium hydroxide. Ligands: A, ethanolamine; B, L-threonine; C, L-serine; D, L-homoserine; E, hydroxyproline.

stability of the complexes formed the interactions of palladium with the side chain of these amino acids can be very clearly demonstrated.[8] It is interesting to investigate if the same situation occurs in the mixed-ligand complexes of palladium with serine, threonine, and other related compounds. With this in mind we have carried out a potentiometric titration study of the interactions of diaqua(ethylenediamine)palladium(II) with L-serine, L-threonine, L-homoserine, L-hydroxyproline, and ethanolamine.

Experimental Section

Materials. The preparation of crystalline $Pd(en)Cl_2$ and $[Pd(en)(OH_2)_2](NO_3)_2$ (en = ethylenediamine) solution therefrom has been reported previously.[9] Serine, threonine, homoserine, and hydroxyproline were obtained from Sigma and were used without further purifications. Since both ethanolamine and its hydrochloride were very hygroscopic, it was converted to its oxalate. For this purpose 12 mL of ethanolamine was mixed with 100 mL of methanol, and to this mixture was added a nearly saturated solution of oxalic acid in methanol until precipitation of the oxalate was complete. The solid was collected and recrystallized from methanol–water mixture. The anhydrous salt crystallized out as large plates with m.p. 196 °C and is nonhygroscopic. Anal. Calcd for $C_6H_{16}N_2O_6$: C, 33.96; H, 7.60; N, 13.20. Found: C, 33.87; H, 7.21; N, 13.01. Elemental analysis was performed by the Australian Microanalytical Service, Division of Applied Organic Chemistry, CSIRO. Standard ethanolamine–HNO_3 solution was prepared from the oxalate by dissolving a known weight of the latter in a small volume of water, and the resulting solution was run through a column of Dowex 2-X8 anion exchanger in the nitrate form. The eluate was collected directly into a standard flask and made up to desired volume. All other chemical used were of AR grade quality.

Potentiometric Titration. (a) $[Pd(en)(OH_2)_2](NO_3)_2$ + Ligands. Potentiometric titrations were carried out on solutions containing a 1:1 molar ratio of $[Pd(en)(OH_2)_2](NO_3)_2$ with the respective ligands at a constant ionic strength medium of 0.1 M KNO_3 at 25 °C, against standard sodium hydroxide. The apparatus and procedure have been described previously.[10] The titration curves are shown in Figure 1. In the case of ethanolamine, titrations were also performed for solutions containing a 1:2 mole ratio of $[Pd(en)(OH_2)_2](NO_3)_2$ to ligand.

(b) Free Ligands. The pK_A and pK_B of the amino acids were determined under the same conditions by titrating weighed samples of the amino acids with standard HNO_3 and NaOH, respectively. The pK_B of ethanolamine was determined by titrating a solution of its hydronitrate against standard NaOH solution.

Table I. Dissociation Constants of Ligands and Stability Constants of Their Complexes with $[Pd(en)(OH_2)_2]^{2+}$ at $I = 0.1$ M (KNO_3) and 25 °C[a]

ligand	pK_A	pK_B	$\log K_1$	pK_1'
ethanolamine		9.62 ± 0.01	7.88 ± 0.02	5.16 ± 0.02
serine	2.27 ± 0.01	9.17 ± 0.01	11.01 ± 0.01	8.51 ± 0.01
threonine	2.25 ± 0.01	9.07 ± 0.01	10.96 ± 0.01	8.05 ± 0.01
homoserine	2.32 ± 0.01	9.39 ± 0.01	11.09 ± 0.02	9.60 ± 0.02
hydroxyproline	1.95 ± 0.01	9.62 ± 0.02	11.47 ± 0.02	10.82 ± 0.02

[a] Initial concentration of $[Pd(en)(OH_2)](NO_3)_2$ is 8.190×10^{-3} M.

Results and Discussions

The ionization of the amino acids may be represented by (1) and (2), where L^-, $HL^{\pm}$, and H_2L^+ are the anionic, zwitterion, and cationic forms of the amino acids.

$$H_2L^+ \rightleftharpoons H^+ + HL^{\pm} \quad (1)$$

$$HL^{\pm} \rightleftharpoons H^+ + L^- \quad (2)$$

For ethanolamine, the ionization is represented by (3).

$$HL^+ \rightleftharpoons H^+ + L \quad (3)$$

Leaving out charges for simplicity, the reactions of $[Pd(en)(OH_2)_2]^{2+}$ with the respective ligands may be represented by

$$[Pd(en)(OH_2)_2] + L \overset{K_1}{\rightleftharpoons} [Pd(en)L] + 2H_2O \quad (4)$$

$$[Pd(en)L] \overset{K_1'}{\rightleftharpoons} [Pd(en)(LH_{-1})] + H^+ \quad (5)$$

where

$$K_1 = [Pd(en)L]/[Pd(en)(OH_2)_2][L]$$

and

$$K_1' = [Pd(en)(LH_{-1})][H^+]/[Pd(en)L]$$

From Figure 1, it can be seen that for serine, threonine, homoserine, and hydroxyproline reactions 4 and 5 take place in two distinct steps as shown by the two well-separated buffer regions. Evaluations of K_1 and K_1' for these systems can therefore be achieved by simple algebraic means. For ethanolamine, since the reactions take place in the same pH region, K_1 and K_1' cannot be evaluated independently. Hence for this system an iterative procedure was employed by using trial values of K_1 and K_1' and the mass balance and electroneutrality conditions to calculate the titrant volume at each titration point. The difference between the calculated and the experimental titrant volumes was then minimized as a least-squares sum by varying K_1 and K_1' systematically. All numerical computations were done on a Univac 1100 computer. The values of $\log K_1$ and pK_1' and the pK's of the ligands are summarized in Table I.

The pK values of the free ligands generally agree well with values reported in the literature.[11] The $\log K_1$ values for the amino acid complexes are all very large and are very similar in magnitude to the corresponding complexes of glycine and other simple amino acids.[12] This is a strong indication that at low pH, serine, threonine, homoserine, and hydroxyproline coordinate similarly to palladium as in glycine, namely, via the amino and the carboxylic groups forming a five-membered chelate ring while the alcohol groups in the side chains of these amino acids do not participate in coordination. The alternative

(8) M. C. Lim, *J. Chem. Soc. Dalton Trans.*, 1398 (1977).
(9) M. C. Lim and R. B. Martin, *J. Inorg. Nucl. Chem.*, **38**, 1911 (1976).
(10) M. C. Lim, *J. Chem. Soc., Dalton Trans.*, 15 (1977).
(11) *Spec. Publ.—Chem. Soc.*, **No. 17** (1964).
(12) M. C. Lim, *J. Chem. Soc., Dalton Trans.*, 726 (1978).

mode of coordination where these amino acids act as tridentate ligands may also be ruled out on the ground of strict requirements of square-planar geometry of palladium in its usual complexes and the expected strength of the palladium ethylenediamine bonds. The log K_1 value of ethanolamine complex is very much smaller than those of the corresponding amino acid complexes; nevertheless, it is still fairly large, which indicates that in this case also the ligand is bidentate. This is confirmed by calculations performed on solutions containing 1:2 mole ratio of $[Pd(en)(OH_2)_2](NO_3)_2$ to ligand, which give the same values of log K_1 and pK_1'. This rules out the presence of $[Pd(en)L_2]$ species (where L = ethanolamine), which is most likely to be present under the conditions if the ligand were monodentate. The smaller log K_1 value may be attributed to the weaker coordinating tendency of an alcohol group compared to a carboxylate group. Charge effect will also be important since the alcohol is neutral whereas the carboxylate group is negatively charged. The resulting charged neutralization upon forming a complex with the positive palladium center is available only to the carboxylate group.

Examination of the pK_1' values for the various complexes reveals that the value for ethanolamine complex is considerably smaller than that for the rest of the complexes. This is consistent with the scheme where the alcohol group in ethanolamine is coordinated to the palladium center whereas those in the side chain of the amino acids remain unattached prior to deprotonation. Due to the donation of the electron pair on oxygen to the metal center the OH bond can be considerably weakened and the ionization of a proton occurs at fairly low pH.

The relative magnitude of the pK' values of serine, threonine, and homoserine complexes may be interpreted as follows. The addition of more than 1 equiv of base/ligand results in the ionization of the alcohol group on the side chain of the amino acid in the palladium complex, which in turns suffers a change in the mode of coordination. Apparently upon deprotonation the negatively charged alkoxide is a better coordinating center than a carboxylate group, which is displaced. The new mode of coordination involves the amino group and the alkoxide group while the carboxylate group remains unattached. This coordination scheme is consistent with the fairly similar value of pK' for serine and threonine complexes but higher value for the homoserine complex. The chelate rings formed by serine and threonine with the palladium center are five-membered whereas for homoserine the ring is six-membered and presumably less favorable. The decrease in the stability of the homoserine complex is thus reflected in the higher value of its pK'. In all these amino acids complexes it may be inferred that at least part of the driving force for the deprotonation of the alcohol group is undoubtedly due to the gain in stability in changing over to a new mode of coordination involving the alkoxide group. Examples of preference for alkoxide group to carboxylate group have been reported for copper complexes of DL-4-amino-3-hydroxybutanoic acid and DL-3-amino-2-hydroxypropanoic acid.[13,14]

In the case of hydroxyproline, because of the high pH value at which deprotonation occurs, its interpretation is subject to greater uncertainty. However with the interposition of the heterocyclic ring, coordination involving the amine and the alkoxide groups to the same metal ion is very unfavorable sterically. The much higher pK_1' value for that complex is consistent with the assumption that there is no change in the mode of coordination upon deprotonation of the alcohol group. The acidity of the alcohol proton could well be due to the inductive effect as a result of electron donation in the rest of the molecule to the palladium center.

From the above, it may be concluded that the coordination of an alcohol group to a metal ion depends on the nature of the rest of the molecule. In ethanolamine because of the absence of competing group it is able to coordinate to the metal ion while still in the protonated form. The resulting complex loses its proton very easily to form the more stable species involving the more strongly coordinating alkoxide group. For serine, threonine, and homoserine only the deprotonated alkoxide group coordinate because of the presence of the carboxylate group which competes effectively with the neutral alcohol group. In hydroxyproline neither the neutral alcohol nor the deprotonated alkoxide group coordinates because of steric reasons.

Acknowledgment. I thank the University of Malaya for a Vote-F Grant.

Registry No. $[Pd(en)(OH_2)_2](NO_3)_2$, 62418-53-5; ethanolamine, 75-39-8; L-serine, 56-45-1; L-threonine, 72-19-5; L-homoserine, 672-15-1; L-hydroxyproline, 51-35-4; ethanolamine oxalate, 15507-86-5; [Pd(en)(ethanolamine)]$^{2+}$, 76648-82-3; [Pd(en)(L-serine)]$^+$, 76648-83-4; [Pd(en)(L-threonine)]$^+$, 76648-84-5; [Pd(en)(L-homoserine)]$^+$, 76648-85-6; [Pd(en)(L-hydroxyproline)]$^+$, 76648-86-7; Pd(en)(L-serine), 76648-87-8; Pd(en)(L-threonine), 76648-88-9; Pd(en)(L-homoserine), 76648-89-0.

(13) A. Braibanti, G. Mori, F. Dallavalle, and E. Leoperati, *J. Chem. Soc., Dalton Trans.*, 1319 (1975).
(14) A. Braibanti, G. Mori, and F. Dallavalle, *J. Chem. Soc., Dalton Trans.*, 826 (1976).