A ^{1}H Nuclear Magnetic Resonance Study of the Deprotonation of L-Dopa and Adrenaline

By **Reginald F. Jameson,* Geoffrey Hunter,** and **Tamas Kiss,** Department of Chemistry, The University, Dundee DD1 4HN, Scotland

The acid–base chemistries of L-3,4-dihydroxyphenylalanine (dopa), L-adrenaline (ad), 3,4-dimethoxyphenylethylamine (dmpe), and 3,4-dihydroxyphenylpropionic acid (dhpa) have been studied by ^{1}H n.m.r. spectroscopy in D_2O solution. Macroscopic dissociation constants for dmpe and dhpa and macroscopic and microscopic dissociation constants for the phenolic OD and the side-chain ammonium groups of dopa and ad have been calculated from the ^{1}H chemical shift titration curves for the aryl and allyl protons by a non-linear least-squares curve-fitting program. The isotope effect on the acidity has been determined for several amines and phenols in order to estimate the microscopic dissociation constants of dopa and ad in H_2O from the values obtained in D_2O. The results indicate that the phenolic hydroxy-groups of dopa and of ad are more acidic than their respective side-chain ammonium groups.

THERE have been several previous reports [1-6] on the dissociation scheme, the measurement of the macroscopic and microscopic dissociation constants, and the assignment of these constants, for catecholamines, There have been, however, differences of opinion regarding the relative acidity of the first phenolic hydroxy and the side-chain ammonium groups of these compounds. The principal method used for a complete resolution of the deprotonation processes was u.v. spectrophotometry,[7] but even the use of the same method by different workers led to different opinions as to the relative acidity of the phenolic OH and ammonium group.[1,2-4] The sensitivity of the chemical shifts and spin–spin coupling constants of nonlabile carbon-bonded protons to the ionization of nearly acidic donor groups makes ^{1}H n.m.r. spectroscopy a possible, more direct method for studying acid–base chemistry at the molecular level [8-10] Granot [6] reported an ^{1}H n.m.r. study of the acid dissociation of different catecholamines and related compounds in D_2O. Recently we have reported [11] preliminary values of the de-deuteronation microconstants of L-3,4-dihydroxyphenylalanine (dopa) determined by the quantitative analysis of its ^{1}H n.m.r. spectra at different pD values.

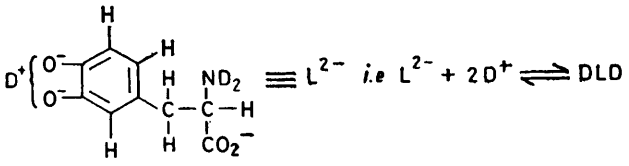
In this paper a complete ^{1}H n.m.r. and potentiometric study of the acid dissociation of L-dopa and L-adrenaline is presented. In order to determine the changes in the chemical shifts of the aryl and alkyl protons of the ligands due to the deuteronation of the phenolic OD and side-chain ND_3^+ groups separately, the de-deuteronation of 3,4-dimethoxyphenylethylamine (dmpe) and 3,4-dihydroxyphenylpropionic acid (dhpa) was also studied. Finally, from these microconstants determined in D_2O, the microconstants in water were estimated by the determination of the isotope effect on the acidity of various amines and phenols.

EXPERIMENTAL

Materials.—Dopa and adrenaline were of the highest purity available from Fluka while 3,4-dimethoxyphenylethylamine and 3,4-dihydroxyphenylpropionic acid were obtained from Aldrich; all were used without further purification. The other chemicals (amines, amino-acids, and phenols) were purified by recrystallization from ethanol–water mixtures or by distillation under reduced pressure as necessary.

Potentiometric Titration.—The dissociation macroconstants of the ligands in D_2O (K^D) and in H_2O (K^H) were determined potentiometrically. 5×10^{-3} mol dm^{-3} solutions were made by dissolving the materials in water and in D_2O (99.8%), both containing 0.10 mol dm^{-3} KNO_3 in order to maintain the ionic strength sensibly constant. 0.1 mol dm^{-3} carbonate- and oxygen-free KOH solutions (in H_2O and in D_2O) were used for the titrations. A 'Radiometer' pHM 64 instrument and GK2301 combination electrode were used, and the pH-meter readings were converted to ion concentrations using the method of Irving *et al.*[12] both in H_2O and in D_2O. All measurements were carried out at 25 ± 0.1 °C.

^{1}H N.m.r. Titration.—The n.m.r. spectra were obtained on a Bruker WP-60 spectrometer at a probe temperature of 25 ± 1 °C. Sodium 3-(Trimethylsilyl)propanesulphonate (DSS) served as internal reference for the shift measurements. Chemical shifts are reported relative to the methyl proton resonance of DSS which was arbitrarily taken as 600 Hz (*i.e.* chemical shifts less than 600 Hz indicate protons less shielded than the methyl protons of DSS). The experimental uncertainity in chemical shifts were of the order ±0.02 Hz. In the samples the concentrations of dopa, dmpe, and dhpa, were 0.02 mol dm^{-3} while that of ad was 0.01 mol

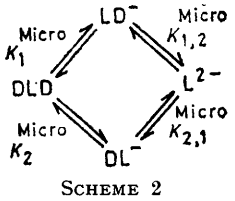


SCHEME 1

dm^{-3}. All solutions between pD 2.5 and 12.5 were prepared from an acidic stock solution by addition of base and all solutions contained 0.10 mol dm^{-3} KNO_3. The pD value of each sample was measured immediately prior to recording the spectrum.

Calculations.—The dissociation macroscopic constants of the ligands were calculated from the potentiometric titrations. Over the pD range 7.0—12.5 deuteronation of the CO_2^- group and the removal of the second OD deuteron may be ruled out, and thus the species treated as a dibasic acid as in Scheme 1 where the second (removable) aryl

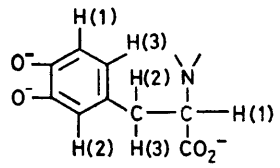
deuteron is written to the left, and the removable amino-deuteron to the right of L. In other words, since only the dissociation of one of the phenolic OD and the side-chain ND_3^+ groups need be considered,[1] the required equilibria are as given in Scheme 2. The first step in the determination of the microconstants is the calculation of the fractional de-deuteronation of each of the two acidic groups as a function of pD from the chemical-shift data.[9] Then the microconstants are calculated from these fractional dissociation data as described earlier,[9,10] by a non-linear least-square curve fitting program.[13]



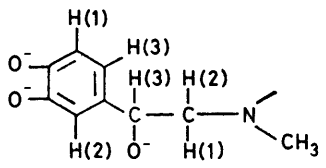
SCHEME 2

RESULTS AND DISCUSSION

The n.m.r. spectrum of dopa consists of two effectively separate ABC multiplets, one arising from the three closely coupled aryl protons and the other from the three closely coupled alkyl protons of the side-chain [see (I)]. The aryl protons of ad give a similar ABC multiplet while the side-chain protons give an AA'X multiplet and a singlet for the NCH_3 group [see (II)]. The numbering scheme for aryl and alkyl protons is also indicated in (I) and (II). Not all lines in the multiplets were resolvable



(I)



(II)

but the line structure of each was almost independent of $[D_3O^+]$ in the pD range 8.0—12.5, whilst the chemical shifts of each proton varied considerably with the dissociation of the OD and the $\equiv ND^+$ deuterons. The spectra recorded at different pD values were analysed *via* the use of the program LAOCOON 3 [14] to obtain accurate chemical shifts and spin–spin coupling constants. The chemical shifts of the protons on the benzene ring and the side-chain carbons of dopa and adrenaline are shown as a function of pD in Figures 1 and 2, respectively, from which it is clear that the side-chain deuterons are being less affected at higher pD than are the phenolic deuterons indicating that the ammonium group is the less acidic. The chemical-shift data and the spin–spin coupling constants of the ligands are given in Table 1 where ν is the chemical shift, J is the spin–spin coupling constant of the deuteronated ligand measured at low pD, $\Delta\nu$ is the total change in chemical shift, and ΔJ in the coupling constant due to complete dissociation. Once the accurate spectral parameters were obtained, band-shape fitting was undertaken by means of the DNMR3 program.[15] A representative experimental and calculated spectrum of dopa is shown in Figure 3 from which it is seen that there is excellent agreement between experiment and calculation.

The fractional dissociation of each of the acidic groups

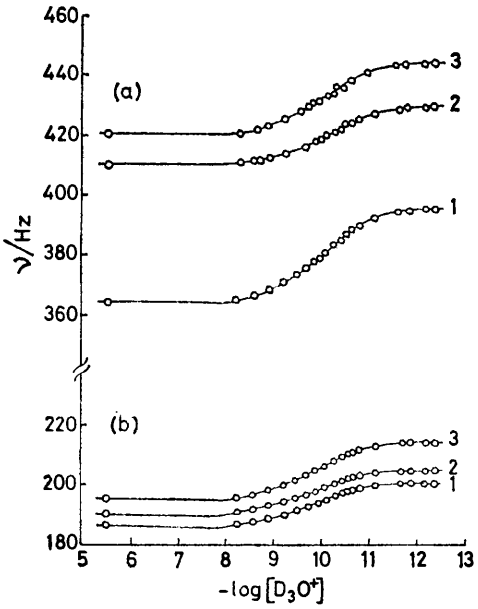


FIGURE 1 pD Dependence of the chemical shifts of the (a) alkyl and (b) aryl protons of dopa

of dopa and adrenaline was determined as a function of pD from the chemical-shift data in Figures 1 and 2. Initially it was assumed that the change in the chemical shift of the aryl protons was due solely to de-deuteron-

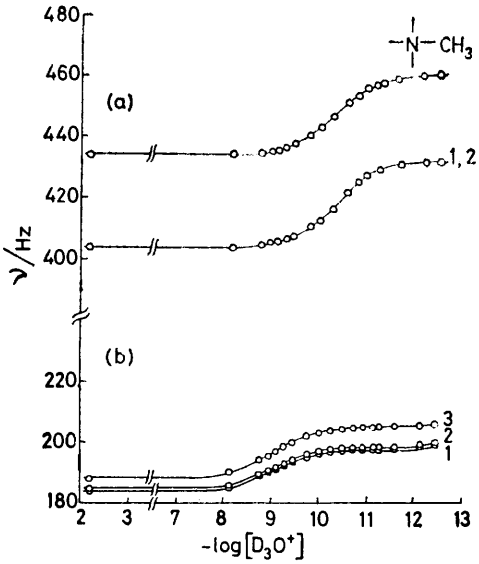


FIGURE 2 pD Dependence of the chemical shifts of the (a) alkyl and (b) aryl protons of adrenaline

ation of the phenolic OD group, whilst the change in the chemical shift of the side-chain protons was entirely due to de-deuteronation of the $\equiv ND^+$ group.[11]

However, as was reported by Sudmeier and Reilley,[16]

the deprotonation of primary amines results in a change in the chemical shift of the γ-protons. This means in our case that the dissociation of the side-chain ammonium group of dopa or of adrenaline almost certainly has an effect on the chemical shift of the *aryl* protons, and similarly, the dissociation of the phenolic OD group has an effect on the chemical shift of *side-chain* protons. For this reason the fractional de-deuteronation curves reported in our previous communication [11] do not reflect entirely the de-deuteronation of a single ammonium or a phenolic OD group. The NCH_3 protons of adrenaline, on the other hand, enable fractional dissociation of the side-chain ammonium group to be calculated directly from the chemical shift data because any dissociation of the phenolic OD group could safely be assumed, we feel, to have no effect on the CH_3 protons. In an attempt to allow for this effect of the dissociation of one group on the chemical shift of the other group, the de-deuteronation of dmpe and dhpa were also studied. In the case of dmpe [see (III)] the effect of the dissociation of the side-chain ammonium group on the aryl protons can be measured, while in the case of dhpa (IV) the effect of the dissociation of the phenolic OD on the side-chain protons can be obtained. The protons were numbered as in (III) and (IV) (with appropriate prefix alkyl or aryl). The total change in the chemical shift of each proton due to de-deuteronation depends upon the change in the electronic structure of the whole molecule which means that the use of dmpe and dhpa as models for taking into account the effect of the ' other group ' in the dissociation of dopa and adrenaline is not an exact method but would seem to be the only method open to us, and considerably more accurate than ignoring the effect altogether.

TABLE 1

^{1}H N.m.r. parameters for L-dopa and L-adrenaline [a]

		Aryl protons					Alkyl protons				
Catecholamine	Proton [b]	ν	$\Delta\nu$	$J_{n.m}$	J	ΔJ	ν	$\Delta\nu$	$J_{n.m}$	J	ΔJ
Dopa	H(1)	186.7	14.0	$J_{1.2}$	−0.7	−0.4	364.6	31.4	$J_{1.2}$	5.0	0.4
	H(2)	190.5	14.4	$J_{1.3}$	8.3	−0.4	410.9	19.1	$J_{1.3}$	8.1	−0.2
	H(3)	195.5	18.7	$J_{2.3}$	2.6	−0.4	420.5	23.7	$J_{2.3}$	−14.8	−1.2
Adrenaline	H(1)	182.9	14.4	$J_{1.2}$	−0.8	−0.4	403.6	29.5	$J_{1.2}$	−14.3	0.4
	H(2)	183.3	14.5	$J_{1.3}$	7.8	−0.4	403.6	29.5	$J_{1.3}$	6.6	0.5
	H(3)	187.5	17.5	$J_{2.3}$	2.4	−0.3	304.4	19.0	$J_{2.3}$	6.0	0.5
	CH_3						434.6	26.6			

[a] The chemical shifts (in Hz) are measured relative to DSS (assigned arbitrarily as 600 Hz). [b] See formulae (I) and (II) for numbering scheme.

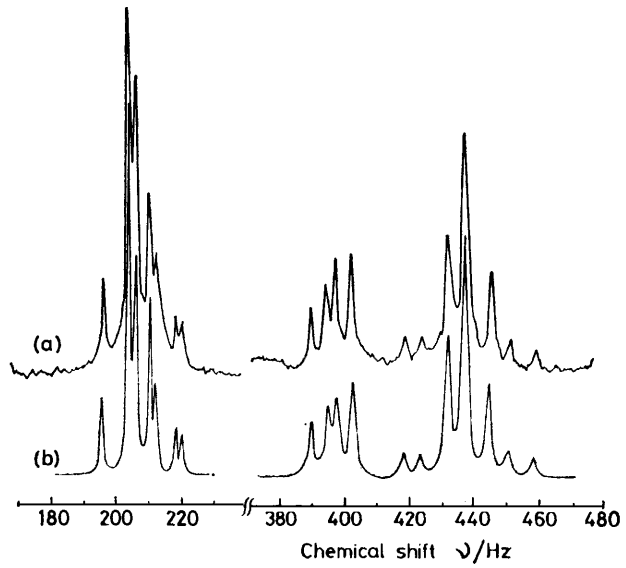
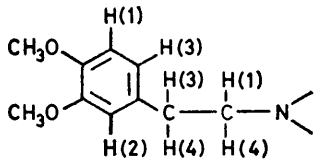
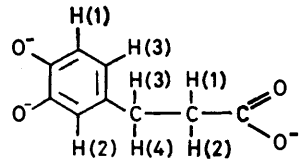


FIGURE 3 60 MHz ^{1}H N.m.r. spectra of dopa in D_2O at 25 °C: (a) experimental, (b) calculated

The aryl part of the ^{1}H n.m.r. spectra of dmpe and dhpa give ABC multiplets, while the side-chain protons give AA'BB' multiplets. As before, the spectra were recorded at different pD values and analysed; the spectral parameters are given in Table 2. It can be seen from the data in Table 2 that the spin–spin coupling constants



(III)



(IV)

vary only slightly over the pD range studied (similar to those of dopa and adrenaline), *i.e.* the populations of different rotamers remain almost constant over the whole pD range.

Thus more accurate values of the fractional dissociation of each functional group of dopa and of adrenaline could be calculated from the chemical-shift data as follows. In equation (1) f_O and f_N are the fractional

$$f_O = \frac{\nu_i^{obs} - \nu_i^{d} - f_N\Delta\nu_{dmpe}}{\nu_i^{p} - \nu_i^{d} - \Delta\nu_{dmpe}} \qquad (1)$$

dissociation of the phenolic OD and side-chain ammonium groups, ν_i^{obs} is the chemical shift observed for the ith proton at a particular pD, ν_i^{p} and ν_i^{d} are the chemical shifts of the ith proton in the fully deuteronated and de-deuteronated forms of the molecule, and $\Delta\nu_{dmpe}$ is the total change (see Table 2) in the chemical shift of the ith proton of the aryl part of dmpe due to dissociation of the side-chain ammonium group.

In equation (2) ν_j^{obs}, ν_j^{p}, and ν_j^{d} are defined as above for the jth proton and $\Delta\nu_{dhpa}$ is the total change in the

chemical shift of the jth proton of dhpa due to dissociation of the phenolic OD group. The initial estimates of f_O and f_N were obtained directly from the chemical shift

$$f_N = \frac{\nu_j^{obs} - \nu_j^{d} - f_O\Delta\nu_{dhpa}}{\nu_j^{p} - \nu_j^{d} - \Delta\nu_{dhpa}} \quad (2)$$

data for the ith and jth proton of dopa and adrenaline. Then iteratively refining f_N and f_O values for each proton of the aryl and alkyl parts of the molecule. This took only a few iteration steps when the f_O and f_N values for each proton of the aryl part and for each proton of the alkyl part agreed with each other within the limits of experimental error. The fractional dissociation of the phenolic OD and the side-chain ammonium groups calculated with this method together with those calculated directly from the chemical shift-data of dopa and adrenaline are shown as a function of pD in Figures 4 and 5, respectively.

The microconstants were then determined by non-linear least-squares curve-fitting the fractional dissociation values to equations (3) and (4). The calculation procedure involved the refinement of K_1^{Micro}, K_2^{Micro}, K_1, and K_1K_2. To check the accuracy of the

$$f_O = \frac{K_1^{Micro}[D^+] + K_1K_2}{[D^+]^2 + K_1[D^+] + K_1K_2} \quad (3)$$

$$f_N = \frac{K_2^{Micro}[D^+] + K_1K_2}{[D^+]^2 + K_1[D^+] + K_1K_2} \quad (4)$$

measurements and the quality of the fit K_1 was calculated from K_1^{Micro} and K_2^{Micro} by use of equation (5).

TABLE 2

^{1}H N.m.r. parameters for dmpe and dhpa [a]

Substance	Aryl protons: Proton [b]	ν	$\Delta\nu$	$J_{n,m}$	J	ΔJ	Alkyl protons: Proton [b]	ν	$\Delta\nu$	$J_{n,m}$	J	ΔJ
dmpe	H(1)	178.6	4.7	$J_{1.2}$	−0.5	−0.7	H(1,2)	402.7	28.0	$J_{1.2;\,3.4}$	−14.0	3.5
	H(2)	181.2	4.0	$J_{1.3}$	8.7	0	H(3,4)	422.1	17.4	$J_{1.3}$	8.2	0.3
	H(3)	184.9	3.8	$J_{2.3}$	1.6	1.3				$J_{1.4;\,2.3}$	7.2	0
										$J_{2.3}$	6.0	0
dhpa	H(1)	189.9	11.3	$J_{1.2}$	−0.7	0.4	H(1,2)	434.5	4.3	$J_{1.2;\,3.4}$	−14.0	0
dhpa	H(2)	193.2	12.0	$J_{1.3}$	8.1	−0.3	H(3,4)	454.7	1.4	$J_{1.3}$	8.5	2.0
	H(3)	196.5	16.9	$J_{2.3}$	2.6	−0.3				$J_{1.4;\,2.3}$	6.8	−0.4
										$J_{2.3}$	8.5	0.5

[a] The chemical shifts (in Hz) are measured relative to DSS (assigned arbitrarily as 600 Hz). [b] See formulae (III) and (IV) for numbering scheme.

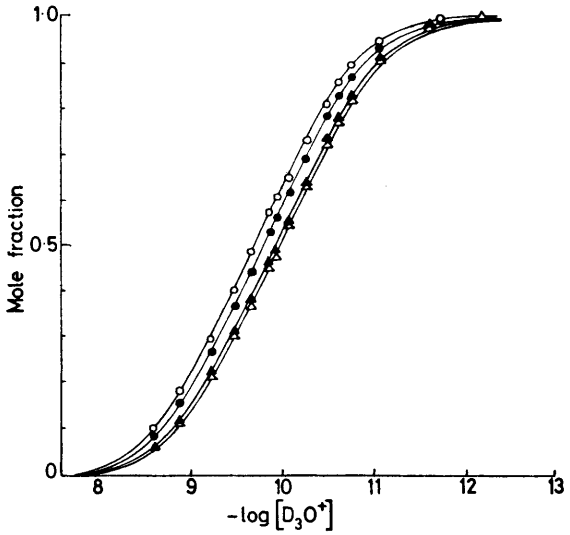


FIGURE 4 Fractional de-deuteronation curves of dopa at the OD site (○) and at the $\overset{+}{N}D_3$ site (△) in D_2O. Full signs indicate direct calculation, open signs corrected with the effect of the ' other group ' (see text)

Microconstants $K_{1,2}^{Micro}$ and $K_{2,1}^{Micro}$ were then calculated from K_1^{Micro}, K_2^{Micro}, and K_1K_2 by use of equation (6).

$$K_1^{Micro} + K_2^{Micro} = K_1 \quad (5)$$

$$K_1^{Micro}\,K_{1,2}^{Micro} = K_2^{Micro}\,K_{2,1}^{Micro} = K_1K_2 \quad (6)$$

The micro- and macro-constants calculated from n.m.r. measurements together with macroconstants calculated from pD titrations are listed in Table 3. The dissociation

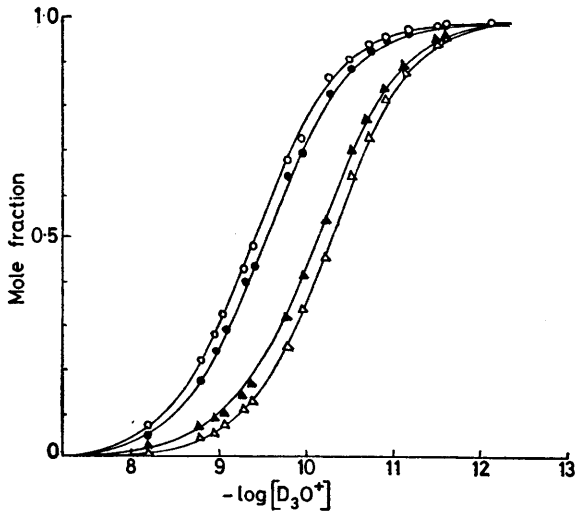


FIGURE 5 Fractional de-deuteronation curves of adrenaline at the OD site (○) and at the $\overset{+}{N}(CH_3)D_2$ site (△) in D_2O. Full signs indicate direct calculation, open signs corrected with the effect of the ' other group ' (see text)

micro- and macro-constants given in Table 3 are higher than those obtained in H_2O solutions.[1] This is due to the isotope effect on acidity [17] resulting in higher values of acidity constants by *ca.* 0.5—0.6 log units for both the

phenolic and ammonium dissociation. Unfortunately, there is no general expression or theory for the isotope effect on acidity. One view is that the ratio of the dissociation constants of the protio- and deuterio-forms of an acid is a function of the strength of the acid, while another is that the ratio is also a function of the type of the acid. Therefore, in order to take the isotope effect into account and obtain values for the microscopic dissociation constants in H_2O, the ionisation constants of several amines and phenols were measured in both solvents. The calculated pK values together with the K^H/K^D values are listed in Table 4 and illustrated in Figure 6.

TABLE 3

pK Values for the de-deuteronation of L-dopa and L-adrenaline in D_2O and 25 °C and containing 0.10 mol dm^{-3} KNO_3

		N.m.r. titration [a]				E.m.f. titration [b]
Dopa	pK_1^{Micro}	9.57				
	pK_2^{Micro}	9.73		pK_1	9.34	pK_1 9.35
	K_1^{Micro}/K_2^{Micro}	1.45				
	$pK_{1.2}^{Micro}$	10.15				
	$pK_{2.1}^{Micro}$	9.99		pK_2	10.39	pK_2 10.40
Adrenaline	pK_1^{Micro}	9.35	9.4 [c]			
	pK_2^{Micro}	9.96	9.9 [c]	pK_1	9.25	9.3 [c] pK_1 9.23
	K_1^{Micro}/K_2^{Micro}	4.09	3.16 [c]			
	$pK_{1.2}^{Micro}$	10.37	10.4 [c]			
	$pK_{2.1}^{Micro}$	9.76	9.9 [c]	pK_2	10.47	10.5 [c] pK_2 10.49

[a] At 25.0 ± 1.0 °C. [b] At 25.0 ± 0.1 °C. [c] See ref. 6.

TABLE 4

pK Values for several amines and phenols in D_2O and in H_2O at 25 ± 0.1 °C and containing 0.10 mol dm^{-3} KNO_3

Ligand	pK^H	pK^D	K^H/K^D
1,3-Diaminopropane (i)	8.83	9.33	3.20
1,3-Diaminopropane (ii)	10.53	11.08	3.61
Phenylalanine	9.09	9.60	3.26
Tryptophan	9.33	9.85	3.28
Ethanolamine	9.52	10.04	3.31
dmpe	9.87	10.39	3.37
2-Phenylethylamine	9.89	10.42	3.38
β-Alanine	10.10	10.64	3.46
Ethylamine	10.68	11.23	3.61
3-Nitrophenol	8.18	8.74	3.62
4-Chlorophenol	9.22	9.81	3.86
dhpa	9.51	10.11	3.91
4-Methylphenol	10.04	10.66	4.10

It can be seen from the Figure 6 that the isotope effect does in fact depend not only upon the strength but also upon the type of acid. However, from these few values no general conclusions can be drawn with regard to the nature of K^H/K^D *versus* pK^H dependence. The isotope effect contribution for the microconstants of dopa and adrenaline can, however, be adequately estimated from these data and are listed, together with some of the literature data, in Table 5.

It is seen clearly from Table 5 that the phenolic hydroxy-groups of dopa and of adrenaline are more acidic than the corresponding side-chain ammonium groups. This is in agreement with Martin,[1] Antikainen and Witikainen,[18] and Granot [6] but in disagreement with Ishimibu *et al.*[3] Comparing our results with those determined spectrophotometrically *via* monitoring the changes in the absorbance of the phenolate group as a function of pH, it can be seen that the spectrophotometric method [1,7] has some value for this type of work provided that oxygen is rigorously excluded. However,

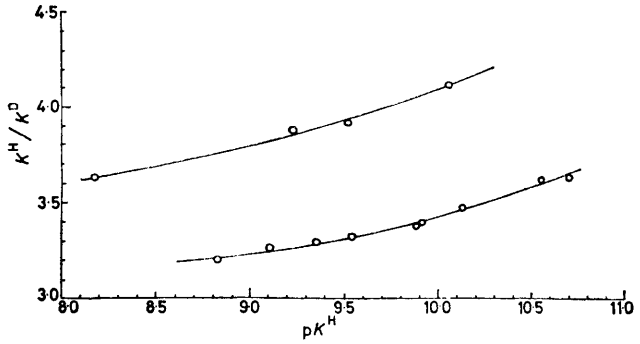


FIGURE 6 K^H/K^D Values of several amines (lower curve) and phenols (upper curve) as a function of pK^H (see Table 4)

TABLE 5

pK Values for the deprotonation of dopa and adrenaline in H_2O

Measured by		N.m.r.[a]	U.v.[b,c]	N.m.r.[a]	U.v.[b,c]	E.m.f. titration [d]
Dopa	pK_1^{Micro}	8.97	9.98 [b]			
	pK_2^{Micro}	9.20	9.19 [b]	pK_1 8.77	8.77 [b]	8.77
	K_1^{Micro}/K_2^{Micro}	1.70	1.62 [b]			
	$pK_{1.2}^{Micro}$	9.61	9.63 [b]			
	$pK_{1.2}^{Micro}$	9.38	9.42 [b]	pK_2 9.81	9.84 [b]	9.79
Adrenaline	pK_1^{Micro}	8.75	8.81 [c]			
	pK_2^{Micro}	9.42	9.39 [c]	pK_1 8.67	8.71 [c]	8.66
	K_1^{Micro}/K_2^{Micro}	4.62	3.80 [c]			
	$pK_{1.2}^{Micro}$	9.82	9.80 [c]			
	$pK_{2.1}^{Micro}$	9.16	9.22 [c]	K_2 9.91	9.90 [c]	9.88

[a] Corrected from data obtained in D_2O, see text; 25 ± 1 °C. [b] See ref. 19; containing 0.2 mol dm^{-3} KCl; 25.0 ± 0.1 °C. [c] See ref. 1; ionic strength 0.1 mol dm^{-3}; 20 °C. [d] Containing 0.1 mol dm^{-3} KNO_3; 25.0 ± 0.1 °C.

it is very difficult to prevent some oxidation, and we feel that this oxidation explains the erroneous results often obtained.[2-4] The n.m.r. techniques score highly in this respect since even moderate oxidation of the compounds results in no error—the value of the chemical shift is independent of concentration—and thus would appear to be a most suitable tool for studies involving protonation (and also conformation and metal complex formation) when multicentre ligands are involved.

We thank the S.R.C. for financial assistance. We are also grateful to Mr. L. Zekany for computational assistance.

[9/1557 *Received*, 1*st October*, 1979]

REFERENCES

[1] R. B. Martin, *J. Phys. Chem.*, 1971, **75**, 2657.
[2] T. Ishimitsu, S. Hirose, and H. Sakurai, *Chem. and Pharm. Bull.* (*Tokyo*), 1976, **24**, 3195.
[3] T. Ishimutsu, S. Hirose, and H. Sakurai, *Talanta*, 1977, **24**, 555.
[4] T. Ishimitsu, S. Hirose, and H. Sakurai, *Chem. and Pharm. Bull.* (*Tokyo*), 1978, **26**, 74.
[5] R. F. Jameson, *J.C.S. Dalton*, 1978, 43.
[6] J. Granot, *FEBS Letters*, 1976, **67**, 271.
[7] J. T. Edsall, R. B. Martin, and B. R. Hollingworth, *Proc. Nat. Acad. Sci. U.S.A.*, 1958, **44**, 505.
[8] D. L. Rabenstein, *J. Amer. Chem. Soc.*, 1973, **95**, 2797.
[9] D. L. Rabenstein and T. L. Sayer, *Analyt. Chem.*, 1976, **48**, 1141.
[10] T. L. Sayer and D. L. Rabenstein, *Canad. J. Chem.*, 1976, **54**, 3392.
[11] R. F. Jameson, G. Hunter, and T. Kiss, *J.C.S. Chem. Comm.*, 1978, 768.
[12] H. M. Irving, M. G. Miles, and L. D. Pettit, *Analyt. Chim. Acta*, 1967, **38**, 475.
[13] L. Zeleany and T. Kiss, unpublished results.
[14] A. A. Bothner-by and S. Castellano, Program 111, Quantum Chemistry Program Exchange, Indiana University.
[15] G. Binsch and D. A. Kleier, Program 140, Quantum Chemistry Program Exchange, Indiana University.
[16] F. L. Sudmeier and C. N. Reilly, *Analyt. Chem.*, 1964, **36**, 1698.
[17] C. K. Rule and V. K. La Mer, *J. Amer. Chem. Soc.*, 1938, **60**, 1974.
[18] P. J. Antikainen and U. Witikainen, *Acta Chem. Scand.*, 1973, **27**, 2075.
[19] A. Gergely, T. Kiss, and Gy. Deak, *Inorg. Chim. Acta*, in the press.