Original Article

^{13}C NMR Spectroscopy on the Complexation of α-Cyclodextrin with 1-Alkanols and 1-Alkanoate Ions

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Abstract

Binding constants for α-cyclodextrin (α-CD) complexes with 1-alkanols and 1-alkanoate ions were determined by analyzing changes ($\Delta\delta$) in chemical shifts of guest ^{13}C NMR signals with α-CD concentration. The guests gave well-separated ^{13}C NMR signals. The curve-fitting analyses of $\Delta\delta$ for individual carbons upon assumption of a simple 1:1 complexation gave virtually the same binding constants (K_1) in the cases of guests with relatively short alkyl chains, such as 1-propanol, 1-butanol, 1-pentanol, 1-butanoate, 1-pentanoate, and 1-hexanoate. However, thus obtained individual K_1 values were significantly different from one another, when the guests had relatively long alkyl chains such as 1-hexanol, 1-heptanol, and 1-octanoate. In these guests, satisfactorily consistent K_1 values were obtained by the curve-fitting analyses of $\Delta\delta$ for individual carbons upon an assumption that not only 1:1 but also 2:1 (host:guest) complexation occurs.

Introduction

Nuclear magnetic resonance (NMR) spectroscopy is useful for the determination of binding constants (K_a) for cyclodextrin (CD) inclusion complexes with organic guest molecules [1]. The chemical shifts (δ's) of ^{1}H's and ^{13}C's involved in the guests are changed in general with the addition of CD by complexation. The K_a values for complexation are determined by the curve-fitting analysis of changes ($\Delta\delta$'s) in the δ's with the concentration of CD. An advantage of this method is that organic guests usually give several independent NMR signals available for the evaluation of K_a. If obtained individual K_a values differ significantly from one another, the fact suggests that the complexation stoichiometry presumed for the calculation is wrong [1]. From this point of view, ^{13}C NMR spectroscopy is preferable to ^{1}H NMR spectroscopy: ^{13}C NMR spectroscopy normally gives such sharp and separated signals that the $\Delta\delta$'s of ^{13}C will independently be observable for all carbons in a guest. On the other hand, the normal ^{1}H NMR spectroscopy of organic guests often gives signals overlapping with one another and with those of CD, so that the protons available for the measurement of $\Delta\delta$ are limited to a few protons.

In order to make use of this advantage of ^{13}C NMR spectroscopy, we examined an effect of α-CD on the $\Delta\delta$'s

of 1-alkanols and 1-alkanoate anions. In these guest molecules, some methylene protons involved gave ^{1}H NMR signals overlapping with one another, and the protons available for the measurement of $\Delta\delta$ were limited to a few protons such as those attached to the terminal methyl group and the α- and β-methylene groups close to the hydroxyl or carboxylate group. Furthermore, the signal due to the α-methylene protons was not available for the measurement of $\Delta\delta$, since it overlapped with those due to added α-CD. On the other hand, all the guests employed in the present study gave several well-separated ^{13}C NMR signals enough to follow $\Delta\delta$'s.

There are several reports in which the K_a values and/or thermodynamic parameters are determined for the complexes of α-CD with 1-alkanols [2–10] and 1-alkanoate ions [8, 11]. However, the results are not always in agreement with one another, and thus this is worthy of further study by means of ^{13}C NMR spectroscopy.

Experimental

The α-CD was supplied by Bio Research Corporation of Yokohama, Ltd., and dried overnight *in vacuo* at 383 K. 1-Alkanols and 1-alkanoic acids employed in the present study were of reagent grade and commercially available. Tetramethylammonium chloride (TMA) used for an

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internal reference in NMR measurement was also commercially available. NMR spectra were recorded using a JEOL Model JNM-A400 FT NMR spectrometer at 298 ± 0.1 K. 1-Alkanols were dissolved in D_2O (Isotec, 99.8 at% D) to give sample solutions for NMR measurements. 1-Alkanoic acids were dissolved in 0.1 mol dm^{-3} Na_2CO_3/D_2O to yield the 1-alkanoate ions. The concentrations of the guests were adjusted to 10 mmol dm^{-3}, unless otherwise noted. TMA (10 mmol dm^{-3}) and methanol (10 mmol dm^{-3}) were used as internal references in the cases of 1-alkanols and the 1-alkanoate ions, respectively. Interactions of TMA and methanol with α-CD are so weak, if any, that these compounds are suitable for internal references in NMR spectroscopy [12]. The δ value for methanol ^{13}C in D_2O was determined to be 51.592 ppm by use of sodium 3-trimethylsilyl-1-propanesulfonate (δ = 0.000) as an internal reference. TMA gave a triplet ^{13}C NMR signal at δ = 57.952 (J = 4.14 Hz) upon using methanol as an internal reference. The splitting is due to spin-spin coupling of the methyl ^{13}C with the ammonium ^{14}N. The binding constants (K_1) for simple 1:1 inclusion complexes of α-CD with guests were determined by a nonlinear least-squares curve-fitting analysis of changes in Δδ with the concentration of α-CD, as described previously [12]. The ^{13}C NMR signals were assigned on the basis of literatures [13, 14].

When 40 mmol dm^{-3} or more α-CD was added to 10 mmol dm^{-3} 1-hexanol, a white precipitate formed. In order to determine the stoichiometry of this precipitate, we separated it by filtration. The residue was dried *in vacuo* and dissolved in dimethyl-d_6 sulfoxide (CEA, 99.8%) containing a trace amount of tetramethylsilane for the measurement of ^1H NMR spectrum.

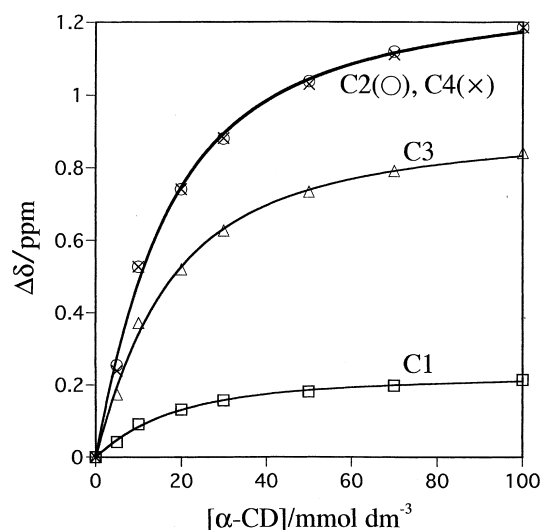*Figure 1.* Changes (Δδ) in ^{13}C NMR chemical shifts for the individual carbons of 1-butanol (10 mmol dm^{-3}) with the addition of α-CD in D_2O at 298 K. Solid lines were obtained by the curve-fitting analysis upon an assumption of simple 1:1 complexation.

Table 1. The individual and average K_1 values (mol^{-1} dm^3) determined by the curve-fitting analysis of relationships between Δδ and c upon an assumption of simple 1:1 complexation of α-CD with 1-alkanols in D_2O at 298 K

Carbon	1-Propanol	1-Butanol	1-Pentanol	1-Hexanol	1-Heptanol
C1	29	86			
C2	27	93	280	640	670
C3	27	90	300	940	1070
C4		92	310	790	2040
C5			370	830	1230
C6				1770	2760
C7					1560
Average	28 ± 1	90 ± 2	320 ± 20	990 ± 200	1560 ± 310

Results and discussion

Complexation of α-CD with 1-alkanols

The binding constants (K_1) for 1:1 complexation of α-CD with 1-butanol have been determined by different methods such as spectrophotometry [2], calorimetry [8], ^1H NMR spectroscopy [9], and surface tension method [10]. Thus, this system is suitable for the test of the versatility of ^{13}C NMR spectroscopy. 1-Butanol gave four ^{13}C signals at δ = 64.27, 36.15, 21.09, and 15.76 due to carbons of C1, C2, C3, and C4, respectively, in D_2O. These signals shifted to a lower-field by the addition of α-CD (Figure 1). The relationships between Δδ's and α-CD concentrations (c) were analyzed by the curve-fitting method, upon the assumption of simple 1:1 complexation of α-CD with 1-butanol. The calculated curves (solid lines) were well-fitted to observed data, and the individual and average K_1 values obtained are summarized in Table 1. They were in good agreement with one another (the average K_1 = 90 ± 2 mol^{-1}dm^3) and with those thus far reported, i.e., 89 mol^{-1}dm^3 [2],

100 kg mol^{-1} [8], 90 ± 5 mol^{-1}dm^3 [9], and 93 ± 20 kg mol^{-1} [10], indicating that the present ^{13}C NMR spectroscopy is available for the determination of K_1. Similarly, we estimated the individual K_1 values for 1:1 complexes of α-CD with 1-propanol, 1-pentanol, 1-hexanol, and 1-heptanol (Table 1). In the case of 1-propanol, the individual K_1 values well agreed with one another, and the average K_1 value (28 ± 1 mol^{-1} dm^3) was in good agreement with those reported, i.e., 23 mol^{-1}dm^3 [2], 27 kg mol^{-1} [8], and 19 ± 1 mol^{-1} dm^3 [9]. In 1-pentanol, the individual K_1 values obtained from the Δδ's of C2–C5 fairly agreed with one another, though that from C5 was somewhat larger than those from C2–C4. The average K_1 value was 316 ± 20 mol^{-1} dm^3, which fairly agreed with those reported, i.e., 324 mol^{-1} dm^3 [2], 275 kg mol^{-1} [8], 434 ± 68 mol^{-1} dm^3 [9], and 378 ± 25 kg mol^{-1} [10]. The Δδ values for the C1 of 1-pentanol were too small to estimate the accurate K_1 value. It has been revealed by ROESY spectra [9] that the CH_3 group (C5) of
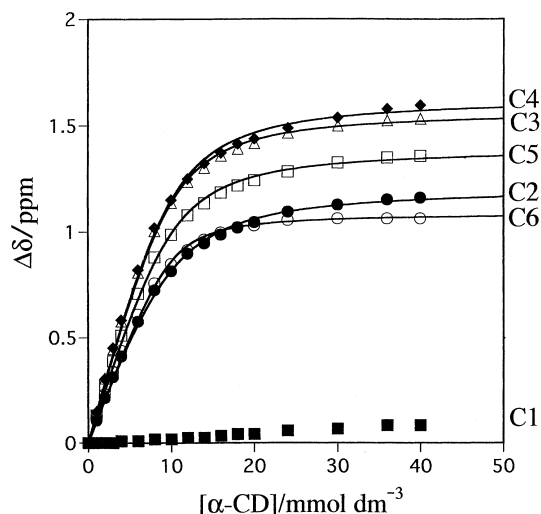
Figure 2. Changes ($\Delta\delta$) in ^{13}C NMR chemical shifts for the individual carbons of 1-hexanol (10 mmol dm^{-3}) with the addition of α-CD in D$_2$O at 298 K. Solid lines were obtained by the curve-fitting analysis upon an assumption of simple 1:1 complexation.

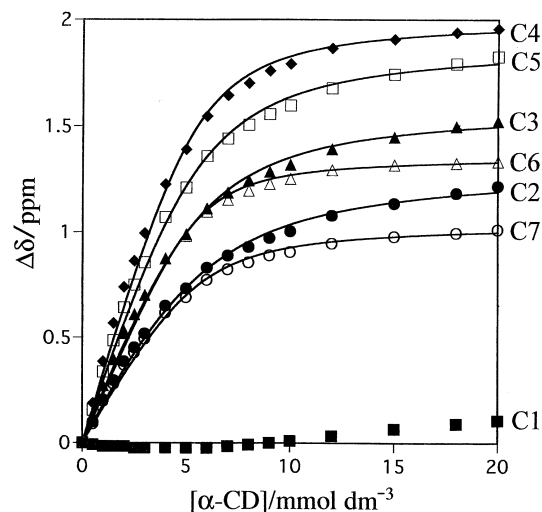*Figure 3.* Changes ($\Delta\delta$) in ^{13}C NMR chemical shifts for the individual carbons of 1-heptanol (5.5 mmol dm^{-3}) with the addition of α-CD in D$_2$O at 298 K. Solid lines were obtained by the curve-fitting analysis upon an assumption of simple 1:1 complexation.

1-pentanol is included at the site close to the narrower rim of α-CD. Then, the C1 of 1-pentanol will protrude to the outside of the α-CD cavity, so that the δ for C1 is little affected by α-CD inclusion.

The results of 1-hexanol and 1-heptanol were remarkably different from those of the lower alkanols (Table 1). In 1-hexanol, the curve-fitting analysis of relationships between $\Delta\delta$ and c for C2–C6 upon an assumption of simple 1:1 complexation gave well-fitted curves with correlation coefficients larger than 0.999. However, the K_1 value obtained from C6 was about twice those from C2–C5. This disagreement in K_1's reflects the fact that the $\Delta\delta$ value for C6 became virtually constant at $c > 20$ mmol dm^{-3}, whereas those for C2–C5 still gradually increased even at $c > 20$ mmol dm^{-3} (Figure 2). Similarly, the plots of $\Delta\delta$ versus c for the C2–C7 of 1-heptanol were significantly different in shape from one another (Figure 3), and thus the K_1 values obtained for C2–C7 upon an assumption of 1:1 complexation were significantly different from one another. These discrepancies in K_1's clearly indicate that the assumption of simple 1:1 complexation is wrong for 1-hexanol and 1-heptanol systems. In such alkanols with relatively long alkyl chains, it will be possible that not only 1:1 complexation but also 2:1 (host:guest) complexation occur. In fact, when 40 mmol dm^{-3} or more α-CD was added to 10 mmol dm^{-3} 1-hexanol, a white precipitate formed. The ^{1}H NMR spectrum of the precipitate in dimethyl-d_6 sulfoxide gave clear signals due to C(1)–H of α-CD at $\delta = 4.80$ (d, $J = 3.2$ Hz) and to CH$_3$ of 1-hexanol at $\delta = 0.86$ (t, $J = 7.1$ Hz). The ratio of peak areas was 12.3:3.0, indicating that two molecules of α-CD is bound to a molecule of 1-hexanol. If 1:1 complexation is followed by 2:1 complexation, we can explain the fact that the $\Delta\delta$ value for C6 of 1-hexanol became virtually constant at $c > 20$ mmol dm^{-3},

whereas those for C2–C5 still gradually increased even at $c > 20$ mmol dm^{-3}, as follows: the terminal CH$_3$ group (C6) of 1-hexanol is deeply included within the α-CD cavity upon 1:1 complexation, and the binding of the second α-CD to the 1:1 complex has a little effect on the magnetic environment of the C6. The other carbons (C1–C5) of 1-hexanol are less deeply included within the α-CD cavity upon 1:1 complexation, and the binding of the second α-CD has appreciable effects on their magnetic environments. In this context, $\Delta\delta$ for C1 is interesting. The $\Delta\delta$ values were very small at $c < 10$ mmol dm^{-3} but obviously showed a gradual increase at $c > 10$ mmol dm^{-3}. The C1 of 1-hexanol will be located at the outside of the α-CD cavity in a 1:1 complex, so that the binding of the first α-CD has a very little effect on its magnetic environment. However, the C1 will be included within the cavity of the second α-CD (Figure 4), and its magnetic environment will change to cause an appreciable increase in the $\Delta\delta$ values. Assuming that the 1:1 complexation is followed by the 2:1 complexation, we analyzed the relationships between $\Delta\delta$ and c for the individual carbons of 1-hexanol and 1-heptanol on the basis of method reported by Funasaki *et al.* [15] to give stepwise binding constants for 1:1 complexation (K_1) and 2:1 complexation (K_2) (Table 2). As shown by the correlation coefficient (r), curve-fit was satisfactorily good for every carbon. Although the obtained individual K_1 values showed some scatter, their relative standard errors were much smaller than those obtained on simple 1:1 complexation (Table 1), indicating that the stepwise complexation mechanism is valid. On the other hand, the individual K_2 values showed significant scatter, probably due to small $\Delta\delta$ caused by 2:1 complexation, compared to large $\Delta\delta$ caused by 1:1 complexation. The average K_1 value for 1-hexanol was 1120 mol^{-1} dm^3, which was slightly
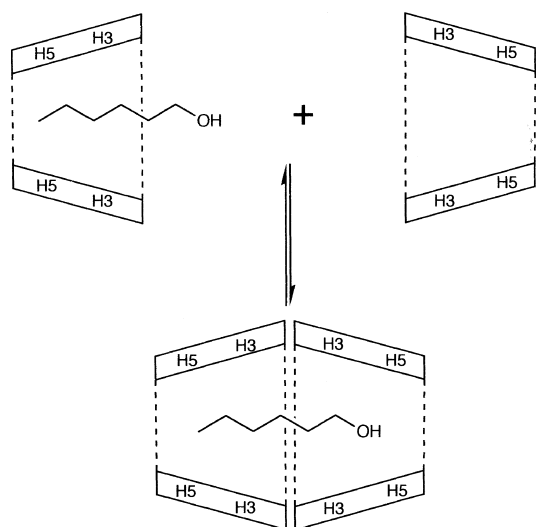
Figure 4. Possible structure of 1:1 and 2:1 complexes of α-CD with 1-hexanol.

Table 3. Differences ($\Delta\delta_{c1}$ and $\Delta\delta_{c2}$) in δ between free and fully complexed guests for 1:1 and 2:1 complexes of α-CD with 1-hexanol and 1-heptanol

Carbon	1-Hexanol		1-Heptanol	
	$\Delta\delta_{c1}$	$\Delta\delta_{c2}$	$\Delta\delta_{c1}$	$\Delta\delta_{c2}$
C1	0.015	0.212	−0.073	0.427
C2	1.105	1.359	1.050	1.674
C3	1.538	1.597	1.396	1.968
C4	1.559	1.796	1.995	1.907
C5	1.347	1.492	1.751	2.090
C6	1.186	0.892	1.395	1.236
C7			1.004	1.102

smaller than that (1331 kg mol^{-1}) measured by calorimetry [8] but significantly larger than the others, i.e., 891 mol^{-1} dm^3 [2] and 698 kg mol^{-1} [10]. The average value for 1-heptanol was 2590 mol^{-1} dm^3, which was larger than those thus far reported, i.e., 2290 mol^{-1} dm^3 [2], 774 kg mol^{-1} [8], and 1270 kg mol^{-1} [10]. The reported lower K_1 values will be caused by neglecting the 2:1 complexation in these guests. Using the thus-determined K_1 values for 1-propanol to 1-heptanol, we obtained a good linear relationship with a correlation coefficient of 0.9978 between log K_1 and the number (N) of carbons in 1-alkanols as follows:

$$\log K_1 = -0.040 + 0.503N. \tag{1}$$

According to Funasaki *et al.* [16], differences ($\Delta\delta_{\text{complex}}$) in δ between free and fully complexed guests provide useful information about the structure of the complex, since $\Delta\delta_{\text{complex}}$ for a proton close to the C(3)–H of α-CD upon complexation shows the maximum value. Thus, we calculated the $\Delta\delta_{\text{complex}}$ values ($\Delta\delta_{c1}$ and $\Delta\delta_{c2}$) for the individual carbons of guests in 1:1 and 2:1 α-CD complexes with 1-hexanol and 1-heptanol, using the

average K_1 and K_2 values (Table 3). In a 1:1 α-CD–1-hexanol complex, the $\Delta\delta_{c1}$ value for C4 was the largest, and the $\Delta\delta_{c1}$ value for C3 was close to that for C4. Upon an assumption that a guest carbon close to the C(3)–H of α-CD shows the largest $\Delta\delta_{\text{complex}}$, similarly to the guest proton, we estimated a structure of the 1:1 complex in which both of C3 and C4 of 1-hexanol are close to the C(3)–H of α-CD. In a 2:1 α-CD–1-hexanol complex, the $\Delta\delta_{c2}$ value for C4 was the largest and significantly different from those for C3 and C5, suggesting the only C4 is close to the C(3)–H of α-CD in a 2:1 complex. This change in location of 1-hexanol within the α-CD cavity will be caused by an attractive force from the second α-CD in the 2:1 complex, as illustrated in Figure 4. In a 1:1 α-CD–1-heptanol complex, the $\Delta\delta_{c1}$ value for C4 was the largest, whereas that for C5 was the largest in a 2:1 α-CD–1-heptanol complex. This result also shows that the second α-CD attracts 1-heptanol to its cavity.

Complexation of α-CD with the 1-alkanoate ions

In order to confirm the utility of the ^{13}C NMR titration method, we further applied it to the complexation of α-CD with alkanoate ions, such as 1-butanoate, 1-pentanate, 1-hexanate, and 1-octanoate, in D$_2$O containing 0.1 mol dm^{-3} Na$_2$CO$_3$. The examined alkanoate ions gave ^{13}C NMR signals well-separated form one another. Similarly to α-CD–1-alkanol systems, we estimated the

Table 2. The individual and average K_1 and K_2 values (mol^{-1} dm^3) determined by the curve-fitting analysis of relationships between $\Delta\delta$ and c upon an assumption of 1:1 and 2:1 complexation of α-CD with 1-hexanol and 1-heptanol in D$_2$O at 298 K

Carbon	1-Hexanol			1-Heptanol		
	K_1	K_2	r^{a}	K_1	K_2	r^{a}
C2	1070	10	0.9995	2600	20	0.9976
C3	1030	1	0.9993	2800	10	0.9980
C4	1070	1	0.9990	2590	25	0.9963
C5	1420	10	0.9990	2510	33	0.9974
C6	1010	76	0.9992	2510	100	0.9977
C7				2500	22	0.9971
Average	1120 ± 80	20 ± 14		2590 ± 50	35 ± 13	

$^{\text{a}}$ Correlation coefficient.

Table 4. The individual and average K_1 values (mol^{-1} dm^3) determined by the curve-fitting analysis of relationships between $\Delta\delta$ and c upon an assumption of simple 1:1 complexation of α-CD with the 1-alkanoate ions in 0.1 mol dm^{-3} Na$_2$CO$_3$ at 298 K

Carbon	1-Butanoate	1-Pentanoate	1-Hexanoate	1-Octanoate
C2	23	120		
C3	16	111	685	775
C4	15	98	729	486
C5		96	746	768
C6			824	668
C7				1756
C8				2273
Average	18 ± 3	106 ± 6	746 ± 29	1120 ± 290

Figure 5. Changes ($\Delta\delta$) in ^{13}C NMR chemical shifts for the individual carbons of 1-octanoate (10 mmol dm^{-3}) with the addition of α-CD in 0.1 mol dm^{-3} Na$_2$CO$_3$/D$_2$O at 298 K. Solid lines were obtained by the curve-fitting analysis upon an assumption of simple 1:1 complexation.

Table 5. The individual and average K_1 and K_2 values (mol^{-1} dm^3) determined by the curve-fitting analysis of relationships between $\Delta\delta$ and c upon an assumption of 1:1 and 2:1 complexation of α-CD with the 1-octanoate ion in 0.1 mol dm^{-3} Na$_2$CO$_3$ at 298 K

Carbon	K_1	K_2	r^{a}
C3	3000	12	0.9953
C4	1490	34	0.9999
C5	2270	3	0.9983
C6	3000	54	0.9958
C7	2990	30	0.9997
C8	3000	51	0.9983
Average	2630 ± 260	31 ± 8	

[a] Correlation coefficient.

Table 6. Differences ($\Delta\delta_{c1}$ and $\Delta\delta_{c2}$) in δ between free and fully complexed guests for 1:1 and 2:1 complexes of α-CD with 1-octanoate

Carbon	$\Delta\delta_{c1}$	$\Delta\delta_{c2}$
C2	0.294	1.562
C3	0.883	1.343
C4	1.461	2.054
C5	1.944	2.705
C6	1.604	2.242
C7	1.352	1.391
C8	0.890	0.913

K_1 value for individual carbons upon an assumption of the simple 1:1 complexation of α-CD with the alkanoates (Table 4). The K_1 values obtained from C1 were omitted from the table, since $\Delta\delta$ values for C1 were always too small to give accurate K_1 values. The K_1 values obtained from C2 for 1-hexanoate and 1-octanoate were also omitted from the table on the same reason. In the case of 1-butanoate, the individual K_1 values well agreed with one another, and the average (18 ± 3 mol^{-1} dm^3) also well agreed with that (15.4 ± 0.4 mol^{-1} dm^3) determined by pH potentiometry [11], though it was significantly different from that (86 ± 14 kg mol^{-1}) determined by calorimetry [8]. Similarly, the individual K_1 values well agreed with one another in the cases of 1-pentanoate and 1-hexanoate. The average K_1 (106 ± 6 mol^{-1} dm^3) for α-CD–1-pentanoate was comparable to those reported, i.e., 145 ± 7 kg mol^{-1} [8] and 75.8 ± 0.6 kg mol^{-1} [11]. The average K_1 (746 ± 29 mol^{-1} dm^3) for α-CD–1-hexanoate was somewhat larger than those reported, i.e., 511 ± 54 kg mol^{-1} [8] and 211 ± 12 kg mol^{-1} [11]. In contrast, the individual K_1 values of 1-octanoate were remarkably different from one another and the standard error was as much as 26% of the average K_1, owing to the fact that the $\Delta\delta$ values for C7 and C8 became virtually constant at $c > 10$ mmol dm^{-3}, whereas those for C3–C6 still gradually increased even at $c > 10$ mmol dm^{-3} (Figure 5). Then, we analyzed the data by the curve-fitting method upon an assumption that 1:1 complexation is followed by 2:1 complexation. The obtained individual and average K_1 and K_2 values were summarized in Table 5. The individual K_1 values well agreed with one another, with a few exceptions, and the average, 2630 ± 260 mol^{-1} dm^3, was significantly larger than those reported, i.e., 1353 ± 111 kg mol^{-1} [8] and 622 ± 26 kg mol^{-1} (at 303 K) [11]. Using the thus-determined K_1 values for 1-butanoate to 1-octanoate, we obtained a linear relationship between log K_1 and the number (N) of carbons in 1-alkanoates as follows (the correlation coefficient = 0.9638):
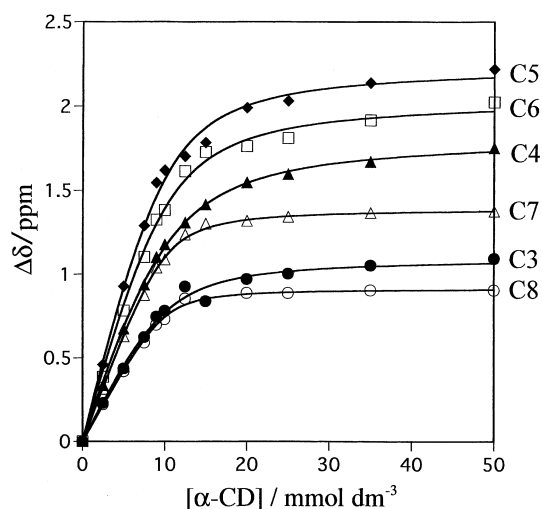
$$\log K_1 = -0.694 + 0.537N. \qquad (2)$$

The slope (0.537) of this equation was close to that (0.503) of Equation (1), indicating that an increment CH$_2$ of 1-alkanoates results in an increase in log K_1 similar to the case of 1-alkanoates. The difference in the intercepts will reflect the hydrophilicity of the functional groups. We also calculated the $\Delta\delta_{c1}$ and $\Delta\delta_{c2}$ values for 1:1 and 2:1 α-CD complexes with 1-octanoate, based on the average K_1 and K_2 values (Table 6). In this case, both of the $\Delta\delta_{c1}$ and $\Delta\delta_{c2}$ values were the largest for the C5 of 1-octanoate, though the latter was significantly

larger than the former. It is notable that the $\Delta\delta_{c2}$ value for C2 was much larger than the corresponding $\Delta\delta_{c1}$ value, indicating that the C2 carbon is included within the second α-CD cavity.

In conclusion, α-CD forms not only 1:1 but also 2:1 complexes with 1-alkanols and the 1-alkanoate ions with relatively long alkyl chains. ^{13}C NMR spectroscopy is thus advantageous not only for the determination of K_1 for α-CD complexes with 1-alkanols and 1-alkanoate ions but also for the inquiry of complexation stoichiometry, since it gives well-separated signals available for the evaluation of individual K_1 values. The K_1 values determined by ^{13}C NMR spectroscopy for 1-alkanols with relatively long alkyl chains in the present study will be more reliable than those determined by absorption spectrophotometry in which only 1:1 complexation was assumed [2].

References

1. H.-J. Schneider, F. Hacket, V. Ruediger, and H. Ikeda: *Chem. Rev.* **98**, 1755 (1998).
2. Y. Matsui and K. Mochida: *Bull. Chem. Soc. Jpn.* **52**, 2808 (1979).
3. M. Maeda and S. Takagi: *Nippon Kagaku Kaishi* 188 (1983).
4. S. Takagi and M. Maeda: *J. Incl. Phenom.* **2**, 775 (1984).
5. H. Fujiwara, H. Arakawa, S. Murata and Y. Sasaki: *Bull. Chem. Soc. Jpn.* **60**, 3891 (1987).
6. S. Takagi, M. Fujisawa, and T. Kimura: *Thermochim. Acta* **183**, 289 (1991).
7. I. Sanemasa, J.-S. Wu, and K. Toda: *Bull. Chem. Soc. Jpn.* **70**, 371 (1997).
8. G. Castronuovo, B. Elia, M. Niccoli, F. Velleca, and G. Viscarde: *Carbohydr. Res.* **306**, 147 (1998).
9. J. Ahmed, T. Yamamoto, and Y. Matsui: *J. Incl. Phenom. Macrocyclic Chem.* **38**, 267 (2000).
10. Y. Saito, K. Watanabe, K. Hashizaki, H. Taguchi, N. Ogawa, and T. Sato: *J. Incl. Phenom. Macrocyclic Chem.* **38**, 445 (2000).
11. R.I. Gelb and L.M. Schwartz: *J. Incl. Phenom. Mol. Recogn. Chem.* **7**, 465 (1989).
12. Y. Matsui and S. Tokunaga: *Bull. Chem. Soc. Jpn.* **69**, 2477 (1996).
13. J.D. Roberts, F.J. Weigert, J.I. Kroschwitz and H.J. Reich: *J. Am. Chem. Soc.* **92**, 1338 (1970).
14. R. Hagen and J.D. Roberts: *J. Am. Chem. Soc.* **91**, 4504 (1969).
15. N. Funasaki, H. Yodo, S. Hada, and S. Neya: *Bull. Chem. Soc. Jpn.* **65**, 1323 (1992).
16. N. Funasaki, S. Ishikawa, and S. Neya, *J. Phys. Chem.* **107**, 10094 (2003).