

Electrospray-ionization mass spectrometric determination of surfactants based on inclusion with α -cyclodextrin

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Abstract Cyclodextrin (CD) is well known to include the lipophilic compounds to form inclusion complexes, because it has a hydrophobic cavity and a hydrophilic outside surface. The CD complexation is useful for determination of particular surfactants by mass spectrometry due to the increase in the weight of surfactant. In this study, the anionic surfactant was determined directly as its CD-complex in methanol/water (1:1) solution by electrospray-ionization mass spectrometry (ESI-MS), while the nonionic and cationic surfactants were determined indirectly from the concentrations of a deprotonated CD ion, which was derived from the uncomplexed CD.

Keywords Cyclodextrin · Surfactant · Determination · Complexation · Electrospray-ionization mass spectrometry · CD-complex

Introduction

Recently, mass spectrometry is often used in a variety of fields, e.g. pharmacy, chemistry and biochemistry, since molecular weight of a certain compound and information about its molecular architecture can be obtained using a small amount of sample, and the measurement is also easy and quick to handle [1–5]. There are various ionization methods in mass spectrometry, such as electronic ionization (EI), fast atomic bombardment (FAB), matrix assisted laser desorption ionization (MALDI) and electrospray

ionization (ESI). ESI and MALDI mass spectrometries are recently used for the identification of macromolecules such as proteins in the fields of medicinal and an environmental chemistry because they are soft ionization methods as compared with the other methods [6–10]. Inclusion complexes, which are formed by weak interaction such as ion-dipole, hydrogen bonding and van der Waals interaction, can be also identified by ESI and MALDI-MS [11–15]. Moreover, ESI-MS is known to have an excellent determination ability and is therefore used as the detector for high-performance liquid chromatography (HPLC) [16]. Thus, the complexation behavior and constants for metal ion complexes of crown compounds have been estimated by ESI-MS [17–20].

Cyclodextrin (CD) is a cyclic D-glucose oligomer with α -1,4 bonding, whose hexamer, heptamer and octamer are called as α -, β - and γ -CD, respectively. CD is well known to form stable inclusion complexes with lipophilic compounds in polar solvents, such as water, because it has a hydrophobic cavity and a hydrophilic exterior [21–25]. Thus, CD can be used as a modifier to increase molecular weights of small organic compound molecules in mass spectrometry [12]. On the other hand, conventional surfactants have both hydrophobic and hydrophilic moieties, and are used for the detergents in water and the phase transfer catalyst, and so on.

In this paper, we describe the inclusion behavior of cyclodextrin for anionic surfactants, the there-by signal isolation of surfactants complexed by CD from uncomplexed surfactants in ESI-MS, which in turn brings about the easy ESI-MS determination of the anionic surfactants in methanol/water mixed solutions. Cationic and nonionic surfactants were also attempted to determine on the basis of the concentration of deprotonated CD which was derived from uncomplexed CD.

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Experimental

Materials

All reagents were of analytical grade. Water was deionized and distilled. Methanol, α -cyclodextrin (α -CD), sodium dodecyl sulfate (SDS), dodecyl trimethylammonium bromide (DTMABr), and Triton X-100 (Triton X) were purchased from Sigma-Aldrich Japan K.K. Maltohexaose (MHO) was purchased from Nacalai Tesque, Inc.

Determination and investigation of CD-complexes with surfactants by ESI-MS

Methanol/water (1:1) mixtures containing various concentrations of α -CD and surfactants were used for the measurements. ESI-MS analyses were carried out in positive and negative electrospray ionization modes, using Finnigan LCQ-Deca. Samples were introduced into ESI-MS by a direct infusion method at 10 μ L/min. The average values and the standard deviations of mass spectral intensities for the 6-time measurements, whose the highest and lowest values were omitted, were calculated from the plots of MS peak intensity versus concentration of surfactants.

Results and discussion

Optimization of determination conditions for CD-complexes with surfactants

ESI parameters, e.g. the mobile phase, flow rate of nitrogen (sheath gas), source temperature, and capillary voltage, were studied in order to obtain the optimum conditions for the identification and the determination of the CD-complexes with surfactants. Several polar solvents as the mobile phase were studied to obtain the maximum and stable sensitivity. In result, methanol/water (1:1) mixed solutions exhibited the highest sensitivity. The other ESI parameters were fixed as following: flow rate of mobile-phase, flow rate of sheath gas, capillary voltage, and source temperature are 10 μ L/min, 80 arb/0.75 MPa, \pm 50 V, and 200 $^{\circ}$ C, respectively.

Complexing behavior of α -CD with anionic surfactant

The complexing behavior of α -CD with sodium dodecyl sulfate (SDS) as an anionic surfactant was examined by ESI-MS in the negative mode. Figure 1b shows the mass spectrum of the solution containing both α -CD and SDS in 1.0×10^{-5} mol dm $^{-3}$ each. The peaks of CD-complex ion with dodecyl sulfate ion [α -CD + DS] $^{-}$, [DS] $^{-}$ and [α -CD – H] $^{-}$, which was obtained by deprotonation of

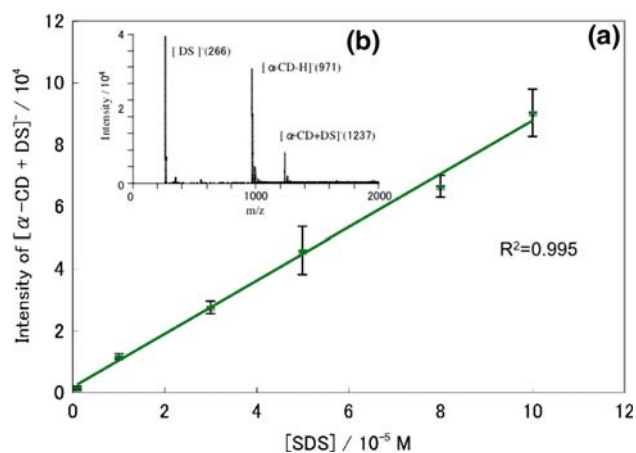


Fig. 1 (a) Plots of peak intensity of CD-complex versus SDS concentration. [α -CD] = 5.0×10^{-4} mol dm $^{-3}$. (b) ESI-MS spectrum of solution containing α -CD and SDS. [α -CD] = 1.0×10^{-5} mol dm $^{-3}$, [SDS] = 1.0×10^{-5} mol dm $^{-3}$

α -CD, were observed by ESI-MS. The peak intensities of α -CD complex ions with SDS were measured in the concentration range between 1.0×10^{-6} and 1.0×10^{-4} mol dm $^{-3}$, keeping α -CD in 5.0×10^{-4} mol dm $^{-3}$. Figure 1a shows the plots of peak intensities of the complex ions against SDS concentrations in the ESI mass spectrum. It was confirmed from the figure that the peak intensity of [α -CD + DS] $^{-}$ was linearly increased with the increase in the SDS concentration. Thus, the concentration of anionic surfactant can be determined as its α -CD complex ion by using ESI-MS [11, 14].

Complexing behavior of α -CD with cationic surfactant

Complexing behavior of α -CD with a cationic surfactant was examined using dodecyl trimethyl ammonium bromide (DTMABr). In the ESI mass spectrum of the solution containing α -CD and DTMABr, no peak assigned to the CD-complex with DTMABr was observed in the positive mode of ESI-MS. Therefore, the determination of the species in the mixed solution using ESI-MS was carried out in negative mode. The typical ESI-MS spectrum for a solution containing α -CD and DTMABr are shown in Fig. 2b. The highest peak is of [α -CD – H] $^{-}$ and the second highest one is of [CD – H + DTMABr] $^{-}$, which is the deprotonated CD-complex ion with DTMABr. However, the peak of [CD – H + DTMABr] $^{-}$ exhibited a very weak intensity and the poor reproducibility. These results showed that the electrically neutral complex of deprotonated α -CD and DTMA $^{+}$, which was derived from DTMABr by the dissociation of Br $^{-}$, is easily formed in the mixed solution of α -CD and DTMABr. The peak intensities of [CD – H + DTMABr] $^{-}$ were measured with changing the DTMABr concentration from 1.0×10^{-6} to 8.0×10^{-5} mol dm $^{-3}$,

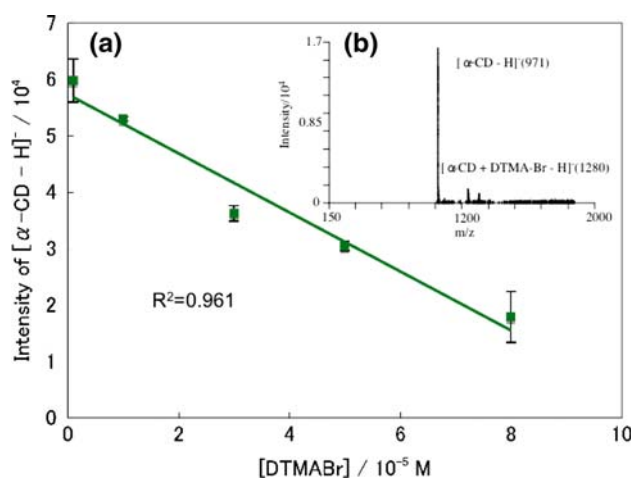


Fig. 2 (a) Plots of peak intensity of α -CD versus DTMABr concentration. $[\alpha\text{-CD}] = 5.0 \times 10^{-5} \text{ mol dm}^{-3}$. (b) ESI-MS spectrum of solution containing α -CD and DTMABr. $[\alpha\text{-CD}] = 1.0 \times 10^{-5} \text{ mol dm}^{-3}$, $[\text{DTMABr}] = 1.0 \times 10^{-5} \text{ mol dm}^{-3}$

keeping α -CD in $5.0 \times 10^{-5} \text{ mol dm}^{-3}$. Its peak intensity was, however, too weak to detect. Therefore, the concentration of deprotonated α -CD, which was decreased by the complexation of deprotonated α -CD and cationic surfactant to form the electrically neutral complex, was measured by the indirect determination of the concentration of cationic surfactant in the solution. The peak intensities of the deprotonated α -CD, $[\alpha\text{-CD} - \text{H}]^-$, were measured by changing the DTMABr concentration from 1.0×10^{-6} to $8.0 \times 10^{-5} \text{ mol dm}^{-3}$ and keeping α -CD in $5.0 \times 10^{-5} \text{ mol dm}^{-3}$. Figure 2a shows the relationship between the peak intensity of $[\alpha\text{-CD} - \text{H}]^-$ and DTMABr concentration in the ESI-mass spectra. The peak intensity of $[\alpha\text{-CD} - \text{H}]^-$ was linearly decreased by the increase in the DTMABr concentration because the concentration of free α -CD decreased by forming the electrically neutral complex with DTMABr. Thus, the concentration of cationic surfactant can be easily determined by measuring the concentration of deprotonated α -CD in negative ESI-MS.

Complexing behavior of α -CD with nonionic surfactant

Complexing behavior of α -CD with a nonionic surfactant was examined using Triton X-100 (Triton X). The typical mass spectrum of a solution containing α -CD and Triton X is shown in Fig. 3b. The peak of $[\alpha\text{-CD} - \text{H}]^-$ was merely observed in the negative mode of ESI-MS, but the complexation of α -CD with the nonionic surfactant could not be detected in the mass spectrum. On the other hand, the peak intensity of $[\alpha\text{-CD} - \text{H}]^-$ was decreased with the addition of Triton X. It is probably because the concentration of α -CD was decreased in the mixed solution due to the formation of the neutral complex between α -CD and Triton X. Therefore, the concentration of nonionic surfactant is determined

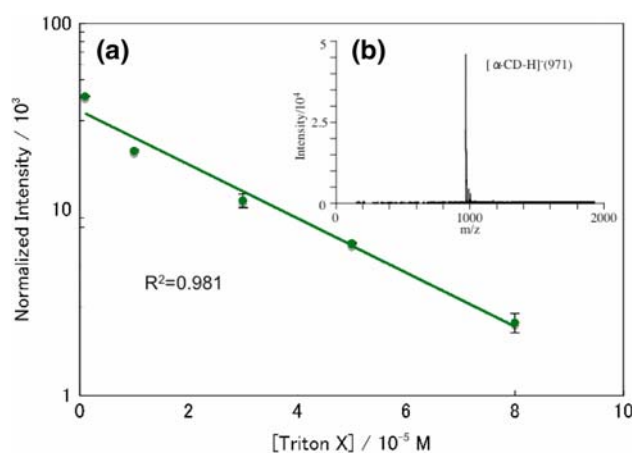


Fig. 3 (a) Plots of peak intensity of α -CD versus Triton X concentration. $[\alpha\text{-CD}] = 1.0 \times 10^{-5} \text{ mol dm}^{-3}$. (b) ESI-MS spectrum of solution containing α -CD and Triton X. $[\alpha\text{-CD}] = 1.0 \times 10^{-5} \text{ mol dm}^{-3}$, $[\text{Triton X}] = 1.0 \times 10^{-5} \text{ mol dm}^{-3}$

indirectly from the change in the peak intensity of $[\alpha\text{-CD} - \text{H}]^-$ on the addition of Triton X. The peak intensities of $[\alpha\text{-CD} - \text{H}]^-$ in the solution containing α -CD in $1.0 \times 10^{-5} \text{ mol dm}^{-3}$ were examined with the increase in the concentration of Triton X from 1.0×10^{-5} to $8.0 \times 10^{-5} \text{ mol dm}^{-3}$. Figure 3a shows the relationship between the peak intensity of $[\alpha\text{-CD} - \text{H}]^-$ and the Triton X concentration in the mass spectra. The peak intensity of $[\alpha\text{-CD} - \text{H}]^-$ was linearly decreased by the addition of Triton X. Therefore, the concentration of nonionic surfactant can be indirectly estimated by the peak intensity change of $[\alpha\text{-CD} - \text{H}]^-$.

Effect of viscosity of nonionic surfactant on peak intensity of $[\alpha\text{-CD} - \text{H}]^-$

The effect of the viscosity of the solution containing α -CD on the peak intensity of $[\alpha\text{-CD} - \text{H}]^-$ was examined with addition of Triton X. For comparison with the case of the α -CD system without any surfactant, the changes in the peak intensities for the ions of *p*-toluenesulfonic acid (*p*-TSA) or tetrabutylammonium chloride (TBACl), which can be measured in the positive mode of ESI-MS, in the concentration of $1.0 \times 10^{-5} \text{ mol dm}^{-3}$ each were examined with an increase in the concentration of Triton X from 1.0×10^{-5} to $8.0 \times 10^{-5} \text{ mol dm}^{-3}$, as shown in Fig. 4.

It was found that the peak intensity of $[p\text{-TSA} - \text{H}]^-$ was hardly decreased as compared with the case of $[\alpha\text{-CD} - \text{H}]^-$, being independent on the concentration change in Triton X. This result shows that Triton X rarely interacts with *p*-TSA and that the viscosity change with the increase in the concentration of Triton X scarcely affected the intensity of $[p\text{-TSA} - \text{H}]^-$. On the other hand, the peak intensity of $[\text{TBA}]^+$, which was observed in the positive

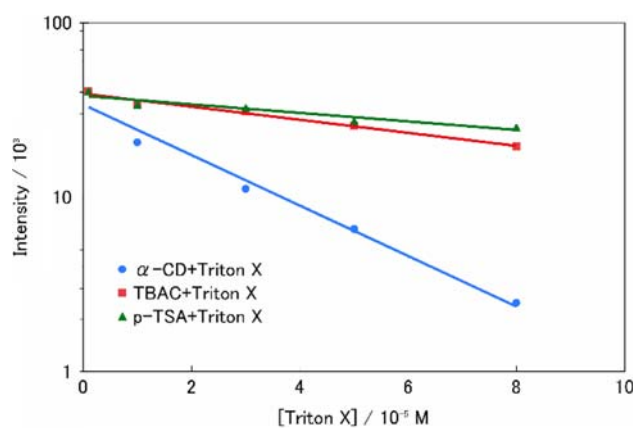


Fig. 4 Plots of peak intensities of $[\alpha\text{-CD} - \text{H}]^-$, TBAC and *p*-TSA versus Triton X concentration. $[\alpha\text{-CD}] = [\text{TBAC}] = [p\text{-TSA}] = 1.0 \times 10^{-5} \text{ mol dm}^{-3}$

mode of ESI-MS, was slightly decreased with the increase in the concentration of Triton X, probably due to the increase in the viscosity of the solution on addition of Triton X.

Thus, the decrease in the peak intensity of $[\alpha\text{-CD} - \text{H}]^+$ with the addition of Triton X was caused by the decrease in the concentration of deprotonated $\alpha\text{-CD}$ due to the complexation between $\alpha\text{-CD}$ and Triton X, and was rarely affected by the viscosity change with addition of Triton X.

Comparison of complexing behavior between $\alpha\text{-CD}$ and MHO with Triton X

Maltohexaose (MHO) is an analogous linear saccharide of $\alpha\text{-CD}$. A mass spectrum of the solution containing MHO and Triton X in $1.0 \times 10^{-5} \text{ mol dm}^{-3}$ each is shown in Fig. 5a. Only a peak of $[\text{MHO} - \text{H}]^-$, which was formed by the deprotonation of MHO, was observed and there was no other peak in the spectrum. For comparison with the case of $\alpha\text{-CD}$, the change in the peak intensities of ions of MHO in $1.0 \times 10^{-5} \text{ mol dm}^{-3}$ was examined with the increase in the concentration of Triton X from 1.0×10^{-5} to $8.0 \times 10^{-5} \text{ mol dm}^{-3}$, as shown in Fig. 5b. The peak intensity of $[\text{HMO} - \text{H}]^-$ was rarely changed by addition of Triton X. It is because MHO hardly forms its complex with Triton X. This in turn causes the decrease in the peak intensity of $[\text{MHO} - \text{H}]^-$. Therefore, the decrease in the peak intensity of $[\alpha\text{-CD} - \text{H}]^-$ in the solution containing $\alpha\text{-CD}$ on the addition of Triton X supports that $\alpha\text{-CD}$ formed the electrically neutral complex with Triton X, the concentration of deprotonated $\alpha\text{-CD}$ being thereby decreased.

Conclusions

In this study, we paid attention to the complexes of $\alpha\text{-CD}$ with anionic, cationic, and nonionic surfactants, and tried to

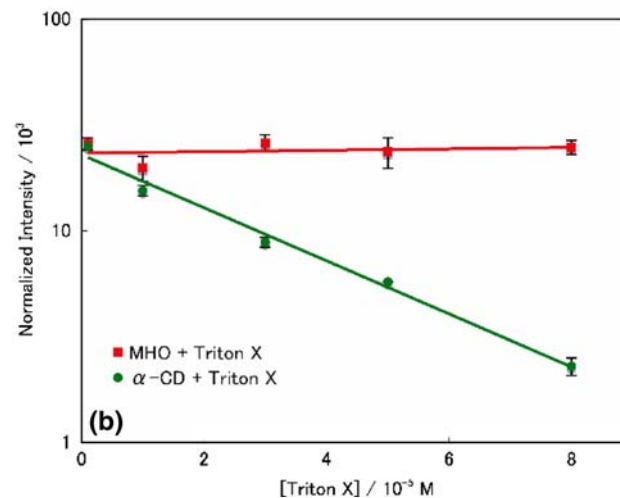
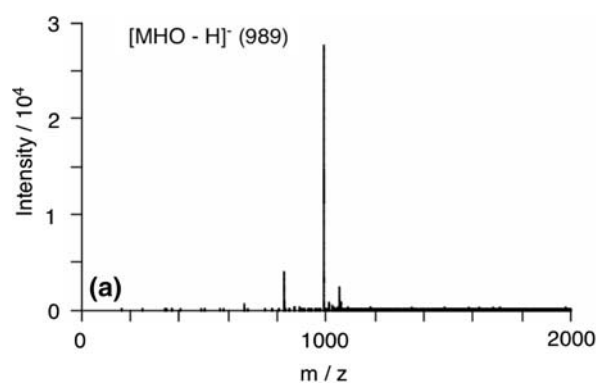


Fig. 5 (a) ESI-MS spectrum of solution containing MHO and Triton X. $[\text{MHO}] = 1.0 \times 10^{-5} \text{ mol dm}^{-3}$, $[\text{Triton X}] = 1.0 \times 10^{-5} \text{ mol dm}^{-3}$. (b) Plots of peak intensity of $\alpha\text{-CD}$ and MHO versus Triton X concentration. $[\alpha\text{-CD}] = 1.0 \times 10^{-5} \text{ mol dm}^{-3}$, $[\text{MHO}] = 1.0 \times 10^{-5} \text{ mol dm}^{-3}$

determine the surfactants using $\alpha\text{-CD}$ as a complexing agent by ESI-MS, taking advantage of the increases in the molecular weight of surfactants by forming its inclusion complex. The peak intensity of CD-complex with anionic surfactant, such as dodecyl sulfate (DS) ion, linearly increased with the increase in the concentration of SDS. Thus, the concentration of anionic surfactant could be measured from the concentration of CD-complex by ESI-MS. On the other hand, the peak intensities of deprotonated $\alpha\text{-CD}$ were linearly decreased with the increase in the concentrations of the cationic and neutral surfactants. Therefore, the concentrations of cationic and nonionic surfactants can be indirectly estimated by the peak intensity change of $[\alpha\text{-CD} - \text{H}]^-$. This method should be a candidate as an analytical method for the laundry drain subsystem.

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