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Application of Double-Reciprocal Plot between the Shift-Length of Absorption Maxima of Solubilized Alkylparabens and Sodium Dodecyl Sulfate Concentration to the Determination of the Distribution Parameter

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In this paper, we discuss the reason why plots of the reciprocal of ([sodium dodecyl sulfate] − cmc) against the reciprocal of the shift-length of the absorption maxima of solubilized alkylparabens show linearity, and what information can be derived from the straight line. Extrapolation of the double-reciprocal plot was utilized to obtain the maximum value of the shift-length, which can not be measured directly. The average of the distribution parameter values can be obtained from the slope of the plot.

Keywords——double-reciprocal plot; distribution parameter; SDS; alkylparaben; wavelength shift; first derivative spectrum; solubilization; micelle

Introduction

The absorption maximum of a drug in surfactant solution often shifts at surfactant concentrations above the critical micelle concentration (cmc). We measured the shift-length (mm) of the maximum absorption wavelength by utilizing the first derivative absorption spectrum. The shift-length is longer when the concentration of surfactant is higher. However, the maximum value of the shift-length is difficult to obtain by measurement because of the existence of the second critical micelle concentration (second cmc) of sodium dodecyl sulfate (SDS). Therefore, we utilized a double-reciprocal plot, and obtained the maximum value of the shift-length from the intercept of the straight line on the ordinate, calculated by the least-squares method. We also calculated the distribution parameter values of the drug between the micellar phase and the bulk phase from the shift-length of the wavelength and ([SDS] − cmc) in the previous report.[1)]

The double-reciprocal plot is used in many fields, and the double-reciprocal plots of the Michaelis–Menten equation, Lineweaver–Burk equation[2)] and Benesi–Hildebrand equation[3,4)] are very well known. The Michaelis–Menten equation and Lineweaver–Burk equation are plots of the reciprocal of the concentration of substrate on the abscissa against the reciprocal of the reaction velocity on the ordinate, and the Benesi–Hildebrand equation is a plot of the reciprocal of the concentration of dye on the abscissa against the reciprocal of the difference absorbance on the ordinate.

In this paper, we discuss the reason why plots of the reciprocal of ([SDS] − cmc) against the reciprocal of the shift-length of the absorption maxima of solubilized alkylparabens show linearity, and what information can be derived from the straight line.

Theory

The system of alkylparaben solubilization with SDS can be expressed as follows.

$$P+(SDS)_m \overset{K}{\rightleftharpoons} P\cdot(SDS)_m$$

where P is alkylparaben (=methyl *p*-hydroxybenzoate (methylparaben), ethyl *p*-hydroxybenzoate (ethylparaben), propyl *p*-hydroxybenzoate (propylparaben) or butyl *p*-hydroxybenzoate (butylparaben)), $(SDS)_m$ is SDS forming micelles, K is the formation constant of the solubilized substance, and $P\cdot(SDS)_m$ is the alkylparaben solubilized in the micellar phase. When $[(SDS)_m]$ is written as

$$[(SDS)_m]=[SDS]-cmc$$

the following equation can be derived,

$$K=[P\cdot([SDS]-cmc)]/[P]\times([SDS]-cmc) \qquad (1)$$

$$[P]_t=[P]+[P\cdot([SDS]-cmc)] \qquad (2)$$

where $[P]_t$ is the total concentration of alkylparaben in this system, and [P] is the concentration of free alkylparaben.

Substituting Eq. 2 into Eq. 1, the following equation can be derived,

$$K=[P\cdot([SDS]-cmc)]/\{[P]_t-[P\cdot([SDS]-cmc)]\}\times([SDS]-cmc)$$

This equation can be rewritten as follows,

$$1/[P\cdot([SDS]-cmc)]=1/K\times[P]_t\times([SDS]-cmc)+1/[P]_t \qquad (3)$$

The equation of the distribution parameter[1] is as follows,

$$K_{dp}=[P\cdot([SDS]-cmc)]\times cmc/([SDS]-cmc)\times[P] \qquad (4)$$

Substituting Eq. 1 into Eq. 4, we obtain

$$K_{dp}=K\times cmc \longrightarrow K=K_{dp}/cmc$$

Substituting K into Eq. 3, the following equation can be derived,

$$1/[P\cdot([SDS]-cmc)]=cmc/K_{dp}\times[P]_t\times([SDS]-cmc)+1/[P]_t \qquad (5)$$

As the degree of shift-length is proportional to $[P\cdot([SDS]-cmc)]$, Eq. 5 multiplied by the proportional constant α gives

$$1/\alpha\times[P\cdot([SDS]-cmc)]=cmc/\alpha\times K_{dp}\times[P]_t\times([SDS]-cmc)+1/\alpha\times[P]_t \qquad (6)$$

Therefore, Eq. 6 defines a straight line when $1/\alpha\times[P\cdot([SDS]-cmc)]$ is plotted on the ordinate against $1/([SDS]-cmc)$ on the abscissa; the intercept is $1/\alpha\times[P]_t$ and the slope is $cmc/\alpha\times K_{dp}\times[P]_t$.

Experimental

Materials——Methylparaben, ethylparaben, propylparaben, butylparaben and SDS (minimum 99%) were obtained from Nakarai Chemicals, Ltd., and potassium chloride (KCl) was obtained from Wako Pure Chemical Ind., Ltd.

Measurement of First Derivative Absorption Spectra——A Hitachi 557 dual-wavelength double-beam spectrophotometer equipped with a Haake-F2C thermostat was used. Measurement conditions were as follows: scale expansion 20 times, scan speed 36 nm/min, slit width 2 nm, scale of absorption spectra from +0.3 to −0.3. Each measurement was repeated at least four times.

Measurement of the cmc of SDS Solution——An electric conductivity meter (CD-35MII, M & S Instruments Inc.) equipped with Tokyo Rikakikai thermostat was used for the measurement of the cmc. The temperature of measurement was 22 °C. A CDC-122 cell was used, and the cell constant obtained by using KCl solution was $4.96\times10^{-4}\,cm^{-1}$ at 22 °C.

Discussion

As the results in the methylparaben–, ethylparaben– and butylparaben–SDS systems are similar to those in the propylparaben–SDS system (Table I), we will present only the results in the propylparaben–SDS system.

A plot of the degree of shift-length *versus* the concentration of SDS is shown in Fig. 1. Since a second cmc of SDS has been reported,[5-7] the value of the maximum shift-length in the first micelles at infinite concentration of SDS can not be obtained directly. We therefore obtained the maximum shift-length by extrapolation of a plot of the reciprocal of the shift-length on the ordinate against the reciproal of ([SDS] − cmc) on the abscissa.

In the previous paper, we calculated the distribution parameter values from the value of the intercept on the ordinate and the following equation

$$K_{dp} = S \times \mathrm{cmc}/(1-S) \times ([\mathrm{SDS}] - \mathrm{cmc}) \qquad (7)$$

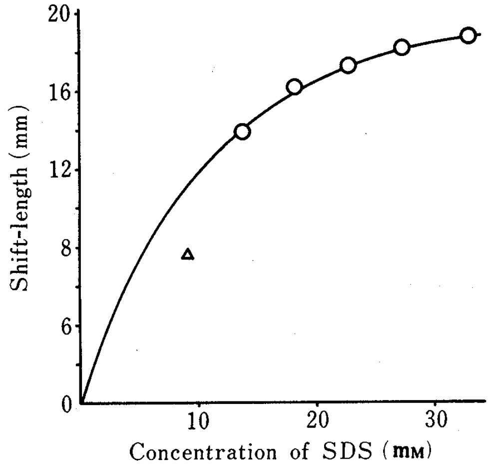

Fig. 1. Curve of Degree of Shift-Length of Propylparaben against Concentration of SDS at 22 °C (Propylparaben = 46.6 μM)

The open triangle shows a point eliminated from the calculation because it is close to the cmc (see the text).

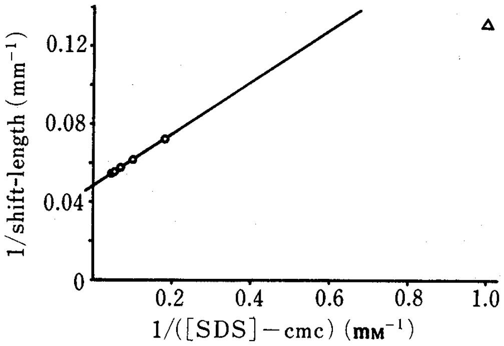

Fig. 2. Double-Reciprocal Plot of ([SDS] − cmc) against Shift-Length of Propylparabbe (Propylparaben = 46.6 μM)

The open triangle shows a point eliminated from the calculation because it is close to the cmc (see the text).

TABLE I. Intercept and Slope of Double-Reciprocal Plots between Shift-Length and ([SDS] − cmc), and Distribution Parameter Values (K_{dp}) at 22 °C

	Intercept (mm^{-1})	Slope ($mM \cdot mm^{-1}$)	K_{dp}
Methyl *p*-hydroxybenzoate	0.056	0.64	0.71
Ethyl *p*-hydroxybenzoate	0.054	0.26	1.7
Propyl *p*-hydroxybenzoate	0.048	0.13	3.0
Butyl *p*-hydroxybenzoate	0.052	0.043	9.9

Methylparaben = 55.2 μM, ethylparaben = 50.6 μM, propylparaben = 46.6 μM, butylparaben = 43.2 μM.

TABLE II. Distribution Parameter Values of Propylparaben

SDS concentration (mM)	13.7	18.2	22.8	27.3	30.3
Distribution parameter	3.0	2.9	2.8	3.1	3.0

S is the degree of shift-length (0–1). On the other hand, the distribution parameter values can also be obtained from the slope ($\mathrm{cmc}/\alpha \times K_{\mathrm{dp}} \times [\mathrm{P}]_t$) of a plot based on Eq. 6. The values of K_{dp} of the 46.6 μM propylparaben–SDS system obtained from Eq. 7 at 22 °C are shown in Table II, and the double-reciprocal plot of the 46.6 μM propylparaben–SDS system at 22 °C is shown in Fig. 2. In Fig. 2, the value of the intercept is 0.0484 mm^{-1}, and the slope is 0.132 $\mathrm{mM}\cdot\mathrm{mm}^{-1}$. Therefore, we have

$$1/\alpha \times [\mathrm{P}]_t = 0.0484$$

$$\mathrm{cmc}/\alpha \times K_{\mathrm{dp}} \times [\mathrm{P}]_t = 0.132$$

The cmc of SDS at 22 °C is 8.1 mM, α is 443.37 $\mathrm{mm}\cdot\mathrm{mM}^{-1}$, and K_{dp} is 2.97. The value of 2.97 is the average of the distribution parameter values at each concentration of SDS.

The double-reciprocal plot, which is a plot of the reciprocal of the shift-length on the ordinate against the reciprocal of ([SDS] − cmc) on the abscissa, can be useful, as described above, but there are regions where it can not be applied. When the concentration of SDS is low and near the cmc (for example, when the concentration of SDS is 9.1 mM), the shift-length can be measured, but the value deviates from the linear relationship (13.7—30.3 mM) (Fig. 2). At this concentration, the micelles may be rather loose, and the environment of the solubilized substances may be different from that at higher concentrations. Therefore, value of shift-length at surfactant concentrations near the cmc should be excluded from the double-reciprocal plot.

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