Chemistry and Physics of Lipids 210 (2018) 14–21

Contents lists available at ScienceDirect

Chemistry and Physics of Lipids

journal homepage: www.elsevier.com/locate/chemphyslip

Uptake of iron (III)-ethylenediamine-*N*, *N*, *N′*, *N′*-tetraacetic acid complex by phosphatidylcholine lipid film. Part II. Effect of film curvature

Masumi Villeneuve[a,*], Mihoko Tanaka[b], Natsumi Saito[b], Hiroyasu Sakamoto[c], Yoshiteru Hayami[d]

[a] *Graduate School of Integrated Arts and Sciences, Hiroshima University, 1-7-1 Kagamiyama, Higashi-Hiroshima 739-8521, Japan*
[b] *Division of Material Science, Graduate School of Science and Engineering, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan*
[c] *Graduate School of Design, Kyushu University, 4-9-1 Shiobaru, Minami-ku, Fukuoka 815-8540, Japan*
[d] *Department of Contemporary Social Studies, Faculty of Contemporary Social Studies, Chikushi Jogakuen University, 2-12-1 Ishizaka, Dazaifu, Fukuoka 818-0192, Japan*

ARTICLE INFO

Keywords:
Phosphatidylcholine
Metal complex
Micelle
pH effect
Curvature effect
Molecular interaction

ABSTRACT

Mixed micelles formed in a ternary-solute aqueous solution of NaOH, iron (III)-ethylenediamine-*N*, *N*, *N′*, *N′*-tetraacetic acid complex (Fe-EDTA) and 1,2-diheptanoyl-*sn*-glycero-3-phosphatidyl choline (DHPC) were studied and compared with the mixed adsorbed film reported in Part I of this series to clarify the effect of the curvature of molecular assemblies on the interactions between their Fe-EDTA and DHPC constituents. The critical micelle concentrations (CMCs), surface tension at the CMC, and solution pH were measured as functions of the mole fractions of NaOH and DHPC. Rigorous thermodynamic equations were derived, in which the overall proton dissociation equilibria of Fe-EDTA and DHPC were taken into consideration, and applied to experimental data to obtain phase diagrams of micelle formation and the micelle-adsorbed film equilibrium. It was found that when the bulk solution was strongly acidic, Fe-EDTA was incorporated in the micelles. However, the adsorbed film was more Fe-EDTA-enriched than the micelle. These findings imply that a flat cell membrane is more permeable to an iron complex than a cell membrane with positive curvature.

1. Introduction

We have studied the surface activity of iron(III)-ethylenediamine-*N*,*N*,*N′*,*N′*-tetraacetic acid complex (Fe-EDTA) under various solution pH conditions Villeneuve et al. (2014) and its miscibility with 1,2-diheptanoyl-*sn*-glycero-3-phosphatidyl choline (DHPC) in the adsorbed film formed at the solution surface. This research was intended to clarify whether an iron-chelator complex could permeate cell membranes. To investigate “Strategy II,” an iron absorption mechanism existing only in graminaceous plants Takagi (1976), it is necessary to assay whether the passive transport (=diffusion) of an iron (III)-mugineic acid complex (Fe-MA) from the rhizosphere through the cell membrane into the cytoplasm is significant. Fe-MA is a fairly stable complex with a nearly octahedral coordination structure and a coordination number of 6 Kato et al. (2011).

In part 1 of this series, we studied the phase diagram of adsorption (PDA) for the ternary-solute aqueous solution of NaOH, Fe-EDTA, and DHPC under different NaOH mole fraction conditions. We used Fe-EDTA as a substitute for Fe-MA because it had a similar coordination structure and the proton dissociation constant. We found that a non-negligible amount of Fe-EDTA was incorporated into the adsorbed film when the NaOH mole fraction was low. With respect to plant physiology, once the iron complex is adsorbed by the DHPC membrane, diffusion of the iron complex into the cell interior may be enabled according to the gradient of the complex concentration.

Lipid molecules have various chemical structures and can assemble into membranes of different curvatures and shapes. The functions and curvatures/shapes of biomembranes are strongly correlated. However, little work has focused on the effect of curvature on the miscibility of metal complexes and lipids in membranes. Herein, we have investigated the miscibility of Fe-EDTA and DHPC in micelles. The results are presented as a phase diagram showing the relationship between the compositions of the micelles and the bulk solution at equilibrium (phase diagram of micelle formation, PDM). The phase diagrams of the micelle-adsorbed film equilibrium were also deduced. Accordingly, the miscibility of Fe-EDTA and DHPC in the micelles was compared with their miscibility in the adsorbed film to understand the curvature effect of the membrane on the uptake efficiency of the iron complex through the rhizo-cell membrane of graminaceous plants.

2. Thermodynamic equation to analyze the micelle solution of a ternary-solute system

The thermodynamic equations for analyzing mixed adsorbed films

---

* Corresponding author.
E-mail address: mville@hiroshima-u.ac.jp (M. Villeneuve).

https://doi.org/10.1016/j.chemphyslip.2017.12.001
Received 10 November 2017; Accepted 2 December 2017

Nomenclature

c0	nonionic Fe complex $[Fe^{III}(H_2O)(HEDTA)]$
c1−	monoanionic Fe complex $[Fe^{III}(H_2O)(EDTA)]^-$
c2−	dianionic Fe complex $[Fe^{III}(OH)(EDTA)]^{2-}$
cd	tetraanionic species formed by olation of c2− $[(edta)Fe^{III}\text{-}O\text{-}Fe^{III}(EDTA)]^{4-}$
$C_{cmc1} = C_{Na^+}$	molality of NaOH at CMC
$C_{cmc2} = C_{c0} + C_{c1-} + C_{c2-} + C_{cd}$	total molality of iron complex at CMC
$C_{cmc3} = C_{DHPC} + C_{DHPC^+}$	total molality of lipid at CMC
C_{cmc}	total molality at CMC
N_i^M	excess number of chemical species i per mixed micelle particle
$N_{c,t}^M = N_{c0}^M + N_{c1-}^M + N_{c2-}^M + 2N_{cd}^M$	total excess number of iron complex per mixed micelle particle
$N_{p,t}^M = N_{DHPC}^M + N_{DHPCH^+}^M$	total excess number of lipid per mixed micelle particle
$N_t^M = N_{Na^+}^M + N_{c,t}^M + N_{p,t}^M$	total excess number per micelle particle
$X_1^M = N_{Na^+}^M/N_t^M$	mole fraction of Na^+ ion in micelle
$X_2^M = N_{c,t}^M/N_t^M$	mole fraction of iron complex in micelle
$X_3^M = N_{p,t}^M/N_t^M$	mole fraction of lipid in micelle
$\Gamma_t^{H,C}$	total surface density at CMC
$X_1^{H,C}$	mole fraction of Na^+ ion in the adsorbed film that is in equilibrium with micelles
$X_2^{H,C}$	mole fraction of iron complex in the adsorbed film that is in equilibrium with micelles
$X_3^{H,C}$	mole fraction of lipid in the adsorbed film that is in equilibrium with micelles

of a ternary system are extended to treat mixed micelles. As in part 1, the dissociation equilibria of Fe-EDTA and DHPC were taken into consideration. The activity coefficients of the ionic components were calculated using the Davies equation Davies (1962). The following electroneutrality condition was employed:

$$m_{H^+} + m_{Na^+} + m_{DHPCH^+} = m_{OH^-} + m_{c1-} + 2m_{c2-} + 4m_{cd} \tag{1}$$

where the subscripts DHPCH$^+$, c1−, c2−, and cd denote DHPC with a protonated phosphate group, the monoanionic species formed from Fe-EDTA $[Fe^{III}(H_2O)(edta)]^-$, the dianionic species $[Fe^{III}(OH)(edta)]^{2-}$, and the tetraanionic dimer $[(edta)Fe^{III} - O - Fe^{III}(edta)]^{4-}$, respectively.

Motomura et al. showed that when the thermodynamic quantities of the micelles are given in terms of excess thermodynamic quantities, similar to those applied to the adsorbed film, they behave similarly to a macroscopic bulk phase. A number of these authors' works have demonstrated that measuring the critical micelle concentration (CMC) of a system as a function of temperature, pressure, and composition provides useful information with respect to micelles. The compositions of NaOH, X_1 and DHPC, X_3, as defined by the following equations, were chosen as the independent experimental variables.

$$X_j = C_{cmcj}/C_{cmc} \tag{2}$$

where $j = 1\text{–}3$, $C_{cmc} = C_{cmc1} + C_{cmc2} + C_{cmc3}$ is the total molality at the CMC, and C_{cmc1}, C_{cmc2}, and C_{cmc3} are the molality of NaOH, and total molalities of Fe-EDTA and DHPC at the CMC, respectively.

At a given temperature and pressure, the mixed micelle solution is described by the analog of Eq. (I. 28) Motomura et al. (1982, 1990):

$$0 = N_{Na^+}^M d\mu_{NaOH} + N_{c,t}^M d\mu_{c0} + N_{p,t}^M d\mu_{DHPC}, \tag{3}$$

with the excess number of constituent component i, regarding micelles

$$N_i^M = N_i/n_m = (n_i - c_i V^W)/n_m. \tag{4}$$

where n_i is the total amount of chemical species i, n_m is the amount of micelles, c_i is the total amount of species i per volume, and V^W is the volume outside the dividing plane, which satisfies

$$N_{H_2O} + N_{OH^-} - N_{Na^+} - N_{cd} = 0. \tag{5}$$

The convention given by Eq. (5) is similar to that chosen for the adsorbed film in part I. The total excess amounts of iron complex species and phospholipid species are defined as sums of the excess numbers of the components originating from Fe-EDTA and DHPC, respectively, as follow:

$$N_{c,t}^M = N_{c0}^M + N_{c1-}^M + N_{c2-}^M + 2N_{cd}^M \tag{6}$$

and

$$N_{p,t}^M = N_{DHPC}^M + N_{DHPCH^+}^M. \tag{7}$$

where c0 notifies the nonionic species $[Fe^{III}(H_2O)(Hedta)]$ of Fe-EDTA. As the total concentrations of the monomeric solutes were nearly equal to the CMC in a limited concentration range, Eq. (3) is rewritten as

$$\begin{aligned} 0= \ &(B^C X_1^M + C^C X_2^M + D^C X_3^M)dC_{cmc} - (E^C X_1^M + F^C X_2^M)dX_1 \\ &+ (H^C X_1^M + I^C X_2^M + J^C X_3^M)dX_3, \end{aligned} \tag{8}$$

where

$$X_1^M = N_{Na^+}^M/N_t^M \tag{9}$$

$$X_2^M = N_{c,t}^M/N_t^M \tag{10}$$

$$X_3^M = N_{p,t}^M/N_t^M \tag{11}$$

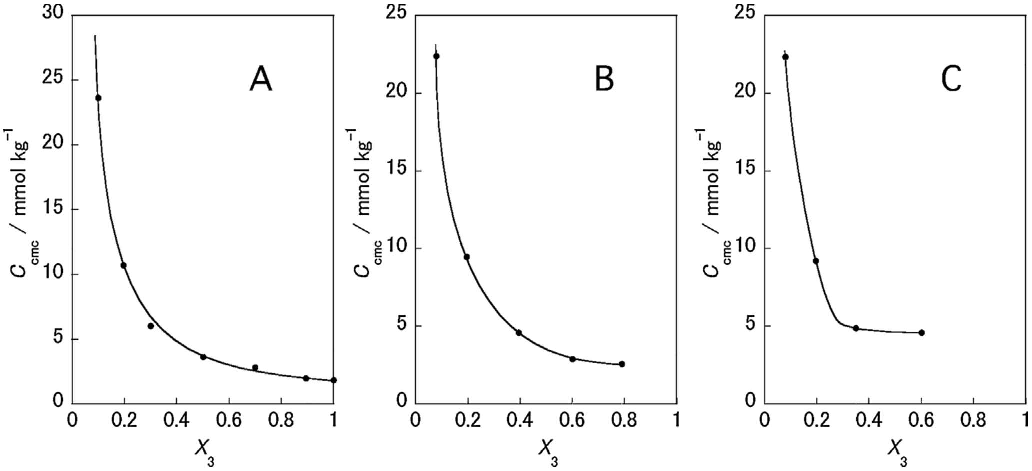

Fig. 1. Critical micelle concentration vs. X_3 at fixed X_1. $X_1 = 0$ (A); 0.211 (B); 0.400 (C). Filled symbols represent the CMC determined from the γ vs. m curves in Figs. 5–7 of Part I.