Lateral Diffusion of Reconstituted Alkylferrocenecarboxamide/Phosphatidylcholine Lipid Monolayer at the Air/Water Interface Studied with Electrochemistry

Jin Soo Kim, Sang Bae Lee,† and Young Soo Kang*

Department of Chemistry, Pukyong National University, Pusan 608-737, Korea

Soo Min Park

Department of Textile Engineering, Pusan National University, Pusan 609-735, Korea

Marcin Majda

Department of Chemistry, University of California, Berkeley, California 94720

JunBoum Park

Department of Civil Engineering, Seoul National University, Shilim-dong, Kwanak-ku, Seoul 151-742, Korea

Received: November 21, 1997; In Final Form: March 24, 1998

Lateral diffusion of alkylferrocenecarboxamide ($FcCONHC_n$)/1,2-dilauroyl-*sn*-glycero-3-phosphatidylcholine lipid monolayer at the air/water interface was determined with electrochemical techniques using a fabricated microline electrode. The prepared homogeneous Langmuir monolayer of electroactive $FcCONHC_n$/phospholipid was identified with pressure−area isotherms in the subphase of 50 mM $HClO_4$. The diffusion constant of electroactive $FcCONHC_n$ in the lipid monolayer was approximately between 0.1×10^{-6} and 2.6×10^{-6} cm^2/s at room temperature. The diffusion constant of ferrocenes in a phospholipid monolayer at the air/water interface was greater for the ferrocene with longer alkyl chains. This is interpreted as the extent of hydrodynamic coupling of the hydrophilic ferrocene moiety of $FcCONHC_n$ to the subphase, which was less for ferrocenes with longer alkyl chains. This lets the position of the hydrophilic headgroup of $FcCONHC_n$ with respect to the air/water interface be shifted upward for the longer alkyl chain because of greater hydrophobic entanglement. The electrochemistry with the microline electrode was possible in the mean molecular area range 60−100 $Å^2$/mol because of monolayer adsorption in a mean molecular area that is less than 60 $Å^2$/mol. The linear decrease of the diffusion constant of ferrocenes with decreasing mean molecular area is explained by the decreasing free volume of the moving headgroup. This is well explained by the modified Cohen−Turnbull free volume model.

Introduction

Biological membranes are highly ordered, heterogeneous molecular assemblies. In the most general sense, a membrane is a continuous mixture of ordered lipids and proteins. This structure is not rigid in nature, but instead, its components are in a constant state of lateral motion. The popular fluid mosaic model of the membrane structure can be thought of as a two-dimensional solution of globular proteins and lipids.[1] The lateral motion of the membrane components is essential to the functioning of the biomembrane systems. The specific molecular structure and composition of the lipid bilayer clearly demonstrate that forms and functions are inextricably intertwined. In such systems, any chemical or physical perturbation may alter the membrane structure and its function. A reorganization of the components to restore its original form can occurr through lateral diffusion of the lipid.[2]

The most important molecular interactions are the noncovalent hydrophobic and hydrophilic interactions with surrounding media and other molecules. The lipids are amphiphilic molecules. In the most energetically favorable structure, the lipids orient themselves with their alkyl chain tails buried in the nonpolar interior and the polar end oriented outward into the aqueous environment. This is defined as the lipid bilayer.

The lateral diffusion of phospholipids and proteins in monolayer and bilayer assemblies has been a subject of considerable interest among biophysicists as a part of broad research on the structure and functioning of cell membranes.[3−8] Extensive investigations of molecular mobility in these types of systems were carried out, in most cases, by fluorescence microphotolysis known as fluorescence recovery after photobleaching (FRAP) techniques.[3−5] The earliest studies concerning the diffusion of lipids in biological membrane systems were carried out using either nuclear magnetic resonance (NMR) and electron spin resonance (ESR) techniques.[9−11] The determined diffusion constant (D) for phospholipids using a spin-labeled probe molecule in the ESR study was known as 10^{-8} cm^2/s. This value has been proved to be reliable in subsequent experiments and has become a basis of comparison for lateral diffusion constants in lipid membranes.

Fluorescence spectroscopy has subsequently become a more popular and useful method in such lateral diffusion determina-

† Current address: Department of Chemistry, KyungNam University, Masan City, KyungNam 631-701, Korea.

S1089-5647(98)00288-0 CCC: $15.00
Published on Web 06/29/1998

tions.[12,13] Among the fluorescence techniques, FRAP has been proven to be fruitful in yielding accurate values of *D* for lipid molecules. FRAP measures the regrowth of fluorescence due to probe molecules diffusing into a pulse photobleached region.[12] Peters and Beck made the most important contribution to the study of lateral diffusion in lipid structures on the water surface using FRAP.[13]

There is a new approach that parallels FRAP in trying to understand lateral transport processes and the fluidity of membranes. This is also to overcome the disadvantages of FRAP because FRAP has some limitations such as convection within the monolayer. This is minimized in the electrochemical technique using a microband electrode. However, the electrochemical method has limitations as well, most notably the need for an electrochemically active probe molecule. The electrochemical technique specifically examines the dynamics of lateral diffusion in Langmuir monolayers at the air/water interface. This technique has its early roots in studies that used electrochemical methods to study the diffusion of amphiphiles in bilayer assemblies.[15] Other concurrent studies also utilized electrochemistry in investigations of Langmuir monolayers, but they did not specifically probe lateral processes.[16] The key to the technique developed is a purposefully designed electrode that can address the monolayer assembly and lateral processes occurring within it. By use of this electrode, the dynamics of lateral transport can be examined because the measured peak current is directly proportional to the arrival rate of the molecules to the electrode surface.

Cyclic voltammetry is used to measure the lateral diffusion constant for the amphiphiles in the monolayer structure. Voltammetric peak current can be used to calculate values of *D* for the system. The peak current is measured by extrapolating a straight line from the baseline and measuring the vertical distance in the cyclic voltammogram. Cyclic voltammograms obtained at the air/water interface during compressions provide a means of obtaining values of *D* while surface concentration was changed. This was done using the previous equation for the voltammetric peak current, i_p, adapted for two dimensions:[17,18]

$$i_p = (2.69 \times 10^5)(n)^{3/2}(l)(D)^{1/2}(\upsilon)^{1/2}(\Gamma)$$

where n is the number of electrons involved, Γ is the surface concentration (mol/cm^2), D is diffusion constant (cm^2/s), υ is scan rate (mV/s), and l is the electrode length (cm). In this model, two dimensions are equivalent to a linear potential sweep voltammetry of a reversible wave in a three-dimensional model.

In the Langmuir monolayer experiments, the surface concentration and physical states of the monolayer can be adjusted while the lateral diffusion processes were examined. When an electron is hopping and the alternative mechanism of charge transport is slow, lateral diffusion becomes the predominant mechanism and the monolayer fluidity can thus be probed.[17,18] This was demonstrated nicely, and the diffusion constant of a ferrocene-substituted amphiphile was measured as a function of surface concentration. This particular set of experiments showed that the diffusivity of the molecules was decreased with decreasing area per molecule. These results were consistent with Peters and Beck's observations. A revised version of the Cohen−Turnbull model was used to explain these results.[17] This model treats the molecules as two-dimensional hard disks in random motion.

In the present study, the electroactive amphiphilic alkylferrocenecarboxamides are used as a probe to investigate the lateral diffusion of the homogeneously mixed monolayer of it in 1,2-dilauroyl-*sn*-glycero-3-phosphatidylcholine fatty acid. The homogeneity was studied with pressure−area isotherms, and the lateral diffusion was studied with electrochemistry using a fabricated microline electrode.

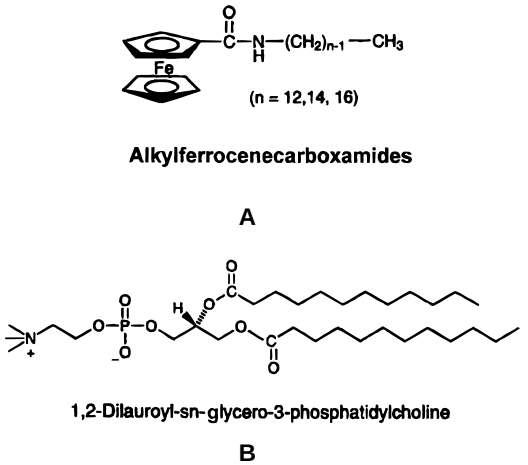

Figure 1. Structures of alkylferrocenecarboxamides (FcCONHC$_n$, n = 12, 14, 16) (A) and 1,2-dilauroyl-*sn*-glycero-3-phosphatidylcholine (B).

Experimental Section

Materials. The electroactive alkylferrocenecarboxamide (FcCONHC$_n$, n = 12, 14, 16), of which structures are shown in Figure 1A, were prepared by modified procedures described previously.[18,19] Dilauroyl-*sn*-glycero-3-phosphatidylcholine fatty acid, of which the structure is shown in Figure 1B was purchased from Avanti Polar Lipids, Inc. and used without further purification. House-distilled water was passed through a four-cartridge Barnstead Nanopure II purification system consisting of macropure pretreatment, organic-free (for removing trace organics), two-ion exchangers and a 0.2 μm hollow-fiber final filter for removing particles. Its resistivity was 18.3 MΩ. Organic solvents such as chloroform, methanol, and glycerol were spectroanalyzed or HPLC grade. The acids used in these experiments were reagent grade and used as received from Fisher.

Trough Setup for Electrochemistry and Pressure−Area Isotherms. The Langmuir trough for both isotherm and electrochemistry experiments (45 cm × 15 cm, KSV model 2200) is housed within a large Plexiglas box to isolate it from laboratory atmosphere, and setups are shown in Figure 2. The trough must be carefully placed to ensure that it was completely level and that there was a good seal between trough and barrier; this is essential to the monolayer compression. These jobs enabled us to keep the experiments from any significant noise for the pressure−area isotherm and electrochemical measurements. The setup includes a surface pressure microbalance that uses the Wilhelmy plate techniques. The movement of the barrier was controlled by a $^1/_{60}$ hp motor (Electro-Craft) and a matching master controller. The KSV system was controlled by a PC-AT clone computer and KSV Dynamic Film Control System Software, Version 2.0. Isotherm compression and data collection were achieved through the use of software. The subphase temperature was controlled with a Fisher Scientific isotope refrigerator circulator, model 900. A compression rate typically used was 20 mm/min which corresponds to 8 (Å^2/molecule)/min. After each experiment at the end of compression, the monolayer was carefully aspirated, and then the subphase was removed before the normal cleaning procedure was used.

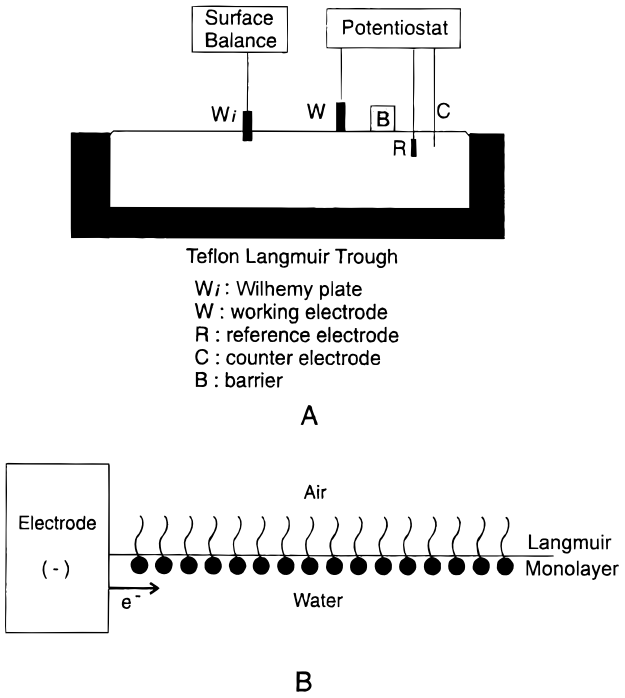

Figure 2. (A) Experimental setup used in the electrochemical measurements of lateral processes in Langmuir monolayer: W, working electrode; B, movable barrier of the Langmuir trough; R, reference electrode; C, counter electrode. (B) Schematic diagram of a microline electrode and its perpendicular orientation with respect to a Langmuir monolayer at the air/water interface.

Fabrication of the Microline Electrodes. The design and special steps taken in the fabrication and preparation of these microline electrode are at the very heart of this electrochemical technique. The MPS (3-mercaptopropyl)trimethoxysilane, Sigma, 97%) layer was formed to promote gold adhesion. Having created a modified glass surface, we can evaporate gold onto the slides. The metal masks used to form the electrode pattern gave six barbell-shaped prints on each slide as shown in Figure 3. Here, the circular contact pads were each 0.2 cm in diameter and the line connecting them was 400 μm in width. Typically, about 900−1050 Å gold (99.999%) films were deposited in a Veeco model 7700 bell jar. The thickness of the coating was measured with a quartz crystal thickness monitor by Kronos Inc., and a typical coating pressure was around 2×10^{-7} to 4×10^{-7} Torr.

The next modification for the hydrophobicity of the electrode surface first was carried out with a self-assembly of octadecylmercaptan (OM), which rendered the gold surface hydrophobic. The next and the most critical step in the electrode fabrication was the self-assembly of octadecyltrichlorosilane (OTS) to create a hydrophobic monolayer on the glass surface. The detailed procedures were described in the previous paper.[20]

Electrochemical Analysis. The same trough, Plexiglas enclosure, and general instrumentation used to record the isotherms were also used in the electrochemical experiments. In this setup, the counter and reference electrodes were placed in special holes in the trough enclosure, which left them below the subphase but not in contact with the water surface, so that the monolayer is not disturbed. The counter electrode was a platinum wire, and a silver wire was used as a quasi-reference electrode. The silver wire has a potential of approximately −150 mV versus SCE. The working electrode was positioned at the air/water interface as shown in Figures 2 and 3 using a movable arm with an electrode clip. To sweep the potential and record the current, a locally constructed model 852 low-current bipotentiostat (Ensman, Inc.) and Kipp-Zone *XYY′t* recorders were used. The monolayer-spreading solutions (2 mM concentration) were prepared fresh daily by weighing and dissolving appropriate amounts of surfactants in chloroform. To spread a surface monolayer of a surfactant, a 32 μL aliquot of a spreading solution was delived in different locations to the subphase surface with a Hamilton gastight microliter syringe.

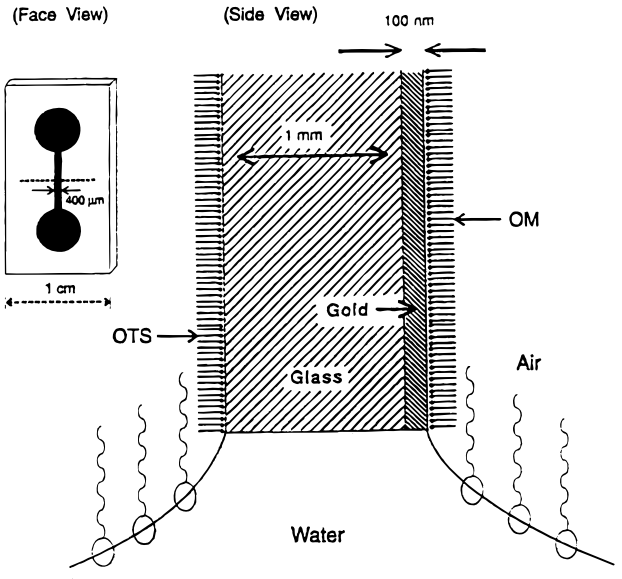

Figure 3. Design of the microline electrode and how it is positioned at the air/water interface. A glass slide with vapor-deposited gold film is marked by the shaded area. The one-dimensional electrode is a 400 mm long line in the plane of the water surface. The bottom edge of the glass slide in contact with water was created by snapping half of the electrode, which initially carried out a twin-pair electrode pattern. All gold and glass surfaces of the glass slide are coated by a self-assembled monolayer of octadecylmercaptan (OM) and octadecyltrichlorosilane (OTS).

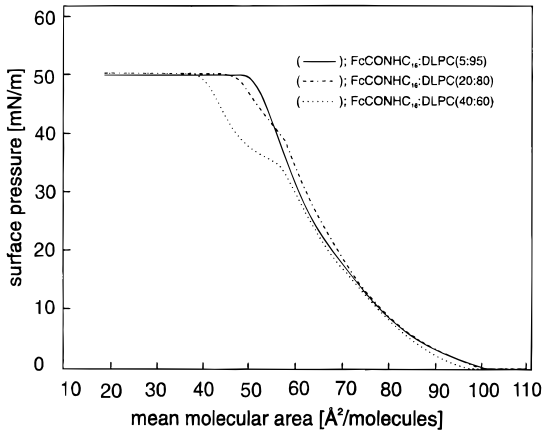

Figure 4. Pressure−area isotherms of $FcCONHC_{16}$/1,2-dilauroyl-*sn*-glycero-3-phosphatidylcholine monolayer with molar ratios of 5/95 (−), 20/80 (−·−), and 40/60 (- - -) in the subphase of 50 mM $HClO_4$ at room temperature.

Results and Discussion

The pressure−area isotherms of each different concentration (5, 20, and 40% molar ratio) of $FcCONHC_n$ in 1,2-dilauroyl-*sn*-glycero-3-phosphatidylcholine in the subphase of 50 mM of $HClO_4$ at room temperature are shown in Figure 4. The pressure−area isotherms with 5% molar ratio of ferrocene to lipid showed the homogeneous phase. The homogeneity of the mixed monolayer at the air/water interface can be investigated

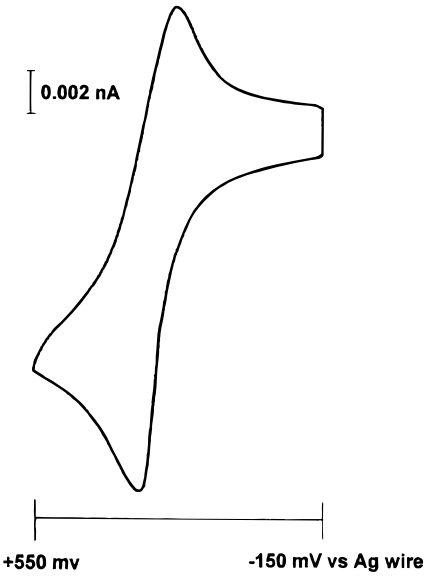

Figure 5. Representative cyclic voltammogram of $FcCONHC_{16}$/1,2-dilauroyl-*sn*-glycero-3-phosphatidylcholine (5/95 molar ratio) monolayer in the subphase of 50 mM $HClO_4$, with 200 mV/s of scan rate, 0.002 nA/cm sensitivity, and 150−700 mV of scan range.

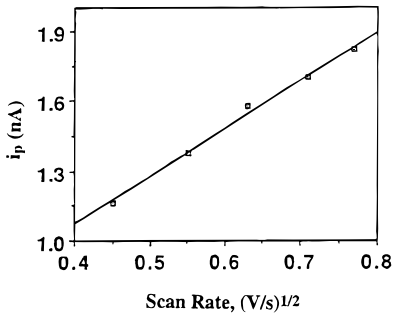

Figure 6. Peak current (nA) of $FcCONHC_{12}$/1,2-dilauroyl-sn-glycero-3- phosphatidylcholine (5/95 molar ratio) monolayer in the subphase of 50 mM $HClO_4$ at room temperature versus scan rate $(V/s)^{1/2}$ data at 98 $Å^2$/molecule.

from the single slope of the isotherms. This results in a single limiting area that is equivalent to the mean molecular area occupied by one molecule at the air/water interface under the supposition of no intermolecular interaction between molecules. The increased molar ratio from 5% to 20% or 40% resulted in inhomogeneous monolayer liquid phases. This is shown by the compressibility change and no single limiting area of their isotherms. The pressure−area isotherm curves do not show any critical difference with changing pendant alkyl chain length of $FcCONHC_n$. The representative cyclic voltammogram of the ferrocene compound in the lipid is shown in Figure 5. The shape of the voltammogram was what would be expected for a linear diffusion case. The diffusion-controlled voltammograms are shown by the peak-to-peak separations for averaged voltages of about 75−80 mV. This indicates that there can be some uncompensated resistance in the system.[21] The peak separation may result from the quasi-reversibility of the ferrocene/ferrocenium couple as well. The linear increase of peak current with increasing $v^{1/2}$ as shown in Figure 6 indicates that the cyclic voltammogram of alkylferrocenecarboxamide in lipids is a diffusion-controlled shape as shown in Figure 6. The results of D versus concentration of $FcCONHC_n$ in the subphase of 50 mM $HClO_4$ are shown in Figure 7. The current studies hope to increase the extent of knowledge of the ferrocene amphiphile system by continuing to study their diffusivity at the air/water

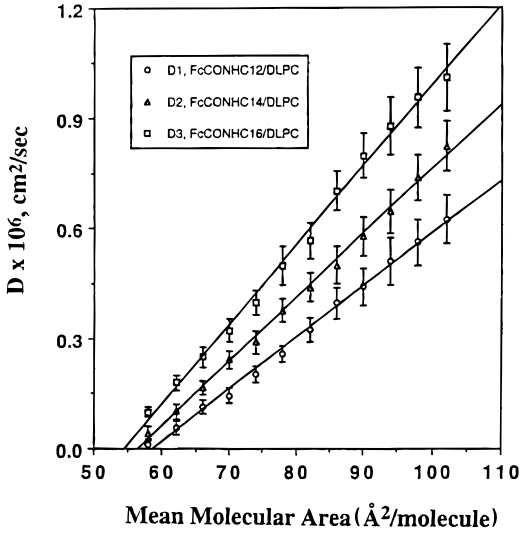

Figure 7. Plot of the diffusion constant D_1 of $FcCONHC_{12}$/DLPC monolayer, D_2 of $FcCONHC_{14}$/DLPC monolayer, and D_3 of $FcCONHC_{16}$/DLPC monolayer with 5/95 molar ratio versus mean molecular area for the different alkylferrocene carboxamide chain length. The data were obtained from the subphase of 50 mM $HClO_4$ at room temperature.

interface.[18−20] This system was shown to be well-behaved and reversible at the air/water interface. The values of the peak current obtained for a particular area per molecule can be used to calculate values of D for the system as outlined previously.[21] The most important finding in this study is that the mechanism of charge transport in the $FcCONHC_n$/lipid monolayers is lateral diffusion.[18,19,22,23] In this study electrochemistry is designed to examine what specifically governs the magnitude of the amphiphile's D at the interface. If something can be learned about the interaction between molecules and the subphase in this manner, then perhaps a similar method can be used to examine the interaction between the amphiphiles at interface. Specifically, how was the molecular diffusion changed with increasing or decreasing alkyl chain length? Can diffusion give clues about the chain−chain hydrophobic interactions and about any increased interaction with increasing alkyl chain length?

This study involved the investigation of three homologous alkylferrocenecarboxamides/phospholipid monolayers that had the same polar headgroup except for the chain length variation of the pendant alkyl chain tail. These particular chain lengths were chosen in order to ensure the stability of the monolayers at the air/water interface. The conditions under which all three ferrocenes/lipid monolayers were exposed to gave well-developed pressure−area isotherms. The isotherms were obtained on an acidic subphase, since the oxidized form of the molecule, ferrocenium, is not stable in neutral pH.[24] All three of the isotherms from dodecyl(C_{12})-, tetradecyl(C_{14})-, and hexadecyl(C_{16})ferrocenecarboxamide (5%)/phosphatidylcholine lipids (95%) have the same shape and general features. The takeoff point is around 105 $Å^2$/molecule. This corresponds to the mean molecolar area at which the monolayer is compressed from a gas/liquid coexistence into a liquid state. The monolayer remains fluid throughout the compression with no apparent phase transition. The pressure at which the monolayer collapses is approximately 50 mN/m for all three derivatives with different alkyl chain lengths. The monolayer with a higher ratio of $FcCONHC_n$ to lipid monolayer (20% and 40%) did not show the homogeneous stable liquid phase as shown in Figure 4. This indicates that the higher ratio of ferrocene derivatives does not distribute evenly in the monolayer because of the limited interaction of ferrocenes with the lipid. The other piece of

information that can be obtained from a pressure−area isotherm is the limiting mean molecular area in the liquid region. This can be determined by extrapolating the steepest part of the isotherm to zero pressure. This value was the same for all three ferrocene/phospholipid monolayers, around 73 Å^2/molecule. This indicates that they all have the same headgroup structure and that the only difference is the alkyl chain length. The limiting mean molecular area corresponds to the cross-sectional area of the phospholipid molecule.[25]

The lateral diffusion of an alkylferrocenecarboxamide/phospholipid monolayer at the air/water interface was studied by determining the peak current of the cyclic voltammogram. The lateral diffusion controls the charge transport along the Langmuir monolayer because charge transport can be controlled by two mechanisms such as lateral diffusion and electron hopping. Lateral diffusion is the sole mechanism of charge transport observed in the alkylferrocenecarboxamide/phospholipid monolayers. This is due to the fact that the electron self-exchange rate constant of the ferrocene/ferrocenium couple systems is too small to compete kinetically with lateral diffusion.[20,26]

For the experimental results shown in the plot of D vs mean molecular area in Figure 7, each of the plots represents the average of three independent series of experiments with standard deviations shown by the error bars. As can be seen in Figure 7, there is a linear decrease of D with decreasing mean molecular area. This can be explained by the Cohen−Turnbull free volume model, which considers the amphiphiles as a two-dimensional hard disk. Lateral diffusion is then analyzed as a random motion of a collection of disks limited only by the fluctuations in free area.[19] Qualitatively, this model states that the molecules move with gas-phase velocity whenever a fluctuation in density creates a void in their cage of residence. From the Cohen−Turnbull model, again adopted for the two-dimensional case, D is given by the following:[14]

$$D = gau \exp(-\gamma A^*/A_f)$$

where g is a geometric factor related to the dimensionality of the system, a and u are the mean displacement and gas-phase velocity of the molecule, γ is a parameter with a value of 0.5−1.0 to correct for overlap of the free area, and A^* and A_f are the critical and free areas per molecule. The free area model has been used successfully to examine the concentration and temperature dependence of lipid diffusion measured by the FRAP technique.[9,27] For example, Peters and Beck used the Cohen−Turnbull model to optimize the linearity of their plots by fitting the limiting mean molecular area of a lipid.

It was shown earlier that when it is assumed that there is no minimum void area necessary and that the system behaves as a fluid at all free areas greater than zero, the equation takes the following linear form:[19]

$$D = guaA_f/\gamma$$

Since many of these parameters are unknown for our system, the model can only be applied in a qualitative manner to show that lateral diffusion is governed by the available free area. This leads to a linear increase of D with A_f. The model neglects all intermolecular interactions and explicitly ignores any hydrodynamic coupling of the amphiphiles to the subphase. These interactions must play a role in the diffusion of the alkylferrocene/phospholipid monolayers at the air/water interface.

The main unprecedented finding in this study is that D increases with increasing chain length at any surface concentration of the ferrocene amphiphiles. These findings are diametrically opposed to what would be expected in view of molecular dynamics studies.[28,29] Calculations done in the previous study reported that the experimental value of D for a ferrocenecarboxamide was more than an order of magnitude smaller than expected by molecular dynamics calculations. The entanglement effect among the alkyl chains, which limited their lateral mobility, was proposed in the previous study.[24] In light of this, the diffusion of these monolayer molecules was supposed to be increased with decreasing chain length. The higher values of decreasing D with increasing alkyl chain length as shown in Figure 7 cannot be explained by the free area model alone. Clearly, a hydrodynamic coupling between the subphase and the amphiphiles must be taken into account to give a more accurate explanation of the lateral diffusion. Specifically, the observed results can be explained by postulating that the extent of the ferrocene/phospholipid monolayer coupling to the subphase was increased as its chain length was decreased. This is possibly explained by the fact that the position of the electroactive ferrocene moiety of shorter alkyl chain length with respect to the air/water interface shifts downward. In other words, it appears that the diffusion of these molecules is affected not only by the lateral interactions covered by the free volume model but also by the viscous coupling of the amphiphiles' polar headgroup to the aqueous subphase. Similar results of lateral diffusion of the alkylferrocenecarboxamide monolayer at the air/water interface with changing alkyl chain length were reported in the previous study.[18,20] In those studies, the postulation on the relative position of the ferrocene moiety with different alkyl chain lengths at the air/water interface was investigated with electrochemistry by changing the subphase viscosity. With longer alkyl chains, there was less effect on the coupling with the diffusion constant change in the subphase viscosity. This was possible under the postulation that the extent of the ferrocene moiety coupling to the subphase was increased as its chain length was increased and that the position of the ferrocene moiety with respect to the air/water interface shifts downward. This suggests that the position of the molecule with respect to the interface is a result of a balance between the hydrophobic portion and hydrophilic interactions. In other words, both the energetics of the hydrophilic headgroup solvation as well as the van der Waals interactions between the alkyl chains have an effect on how the molecule is positioned.[30] These results also seem to indicate that the enthalpy of solvation becomes more negative as the molecule's position with respect to the interface is lowered. All these pieces of information seem to be consistent with the recent molecular dynamic calculations of monolayers at the air/water interface, which show considerable water penetration into the headgroup region as well as an increase in the width of the water interfacial region when compared with a clean air/water interface.[31] The results of the present study are consistent with the previous studies. The higher values of decreasing D with increasing alkyl chain length is possibly explained by the decreased hydrodynamic coupling of the hydrophilic electroactive ferrocene moiety to the subphase. This can be explained by the upward shifts of the ferrocene moiety due to the increased hydrophobic entanglement of longer alkyl chains.

Conclusively, the homogeneous Langmuir monolayer of the FcCONHC$_n$/phospholipid was prepared with a molar ratio of 5/95 (ferrocene/phospholipid). The higher molar ratio resulted in an inhomogeneous monolayer. The decreasing D versus decreasing mean molecular area is explained by the decreasing free area of the monolayer molecules at the air/water interface. The free area increases the lateral diffusion of the electroactive

ferrocene molecule in the phospholipid monolayer. The greater D with the longer alkyl chain length $FcCONHC_n$ in the phospholipid monolayer can be explained by the decreased extent of the hydrophilic headgroup coupling to the subphase because the position of the molecule with respect to the air/water interface shifts upward.

Acknowledgment. This research is supported by Korea Science and Engineering Foundations (Project No. 971-0305-029-2).

References and Notes

(1) Singer, S. J.; Nicolson, G. L. *Science* **1972**, *175*, 720.
(2) Edidin, M. In *Molecular Motions and Membrane Organization and Function*; North-Holland Biomedical Press: Amsterdam, 1981; Chapter 2.
(3) Cherry, R. J. *Biochim. Biophys. Acta* **1979**, *559*, 289.
(4) Peters, R. *Cell Biol. Int. Rep.* **1981**, *5*, 733.
(5) Cadenhead, D. A. In *Structure and Properties of Cell Membranes*; Benga, G., Ed.; CRC Press: Boca Raton, FL; Vol. 3, 1985; p 21.
(6) Edidin, M. In *Membrane Structure*; Finean, J. B., Michell, R. H., Eds.; Elsevier: New York; 1981; Chapter 2, p 37.
(7) Vaz, W. L. C.; Derzko, Z. I.; Jacobson, K. A. *Cell Surf. Rev.* **1982**, *8*, 83.
(8) Wade, C. G. In *Structure and Properties of Cell Membranes*; Benga, G., Ed.; CRC Press: Boca Raton, FL; Vol. 1, 1985; p 51.
(9) Trauble, H.; Sackmann, E. *J. Am. Chem. Soc.* **1972**, *94*, 4499.
(10) Kornberg, R. D.; McConnell, H. M. *Proc. Natl. Acad. Sci. U.S.A.* **1971**, *68*, 2564.
(11) Cherry, R. I. *Biochim. Biophys. Acta* **1979**, *559*, 289.
(12) Tessie, J.; Tocanne, J.; Baudra, A. *Eur. J. Biochem.* **1978**, *83*, 77.
(13) Peters, R.; Beck, K. *Proc. Natl. Acad. Sci. U.S.A.* **1983**, *80*, 7183.
(14) Turnbull, D.; Cohen, M. H. *J. Chem. Phys.* **1970**, *52*, 3083.
(15) Miller, C. J. Ph.D. Thesis, University of California, Berkeley, CA, 1987.
(16) Zhang, X.; Bard, A. J. *J. Am. Chem. Soc.* **1989**, *111*, 8098.
(17) Turnbull, D.; Cohen, M. H. *J. Chem. Phys.* **1970**, *52*, 3083.
(18) Kang, Y. S.; Majda, M. *Mol. Electron. Mol. Electron. Devices* **1995**, *6*, 25.
(19) Charych, D. H.; Landau, E. M.; Majda, M. *J. Am. Chem. Soc.* **1991**, *113*, 3340.
(20) Kang, Y. S.; Majda, M. *J. Phys. Chem.*, submitted.
(21) Bard, A. J.; Faulkner, L. R. *Electrochemical Methods*; John Wiley & Sons, Inc.: New York, 1980.
(22) Charych, D. H.; Goss, C. A.; Landau, E. M.; Majda, M. *Mol. Cryst. Liq. Cryst.* **1990**, *190*, 95.
(23) Majda, M. *Thin Films* **1995**, *20*, 331.
(24) Charych, D. H. Ph.D. Thesis, University of California, Berkeley, CA, 1991.
(25) Gunstone, F. D.; Norris, F. A. *Lipid in Foods Chemistry, Biochemistry and Technology*; Pergamon: New York, 1983.
(26) Neilson, R. M.; McManis, G. E.; Stafford, L. K.; Weaver, J. J. *J. Phys. Chem.* **1989**, *93*, 2152.
(27) Galla, H. J.; Hartman, W.; Theilen, U.; Sackman, E. U. *J. Membr. Biol.* **1979**, *48*, 215.
(28) Wilson, M. A.; Pohorille, A.; Pratt, L. R. *J. Phys. Chem.* **1987**, *91*, 4873.
(29) Dluhy, R. A.; Cornell, D. G. In *Fourier Transform Infrared Spectroscopy in Clooid and Interface Science*; Scheuing, D. R., Ed.; American Chemical Society: Washington, DC, 1991; Chapter 11.
(30) Pohorille, A.; Benjamin, I. *J. Phys. Chem.* **1993**, *97*, 2664.
(31) Pohorile, A.; Wilson, M. *J. Mol. Struct.* **1993**, *284*, 271.