LETTER TO THE EDITOR

Comments on "Electrical Breakdown of Bimolecular Lipid Membranes as an Electromechanical Instability"

Dear Sir:

An interesting analysis of the electrical breakdown of thin lipid films was presented by Crowley (1973). He assumed the film to be a bulk elastic layer that can be deformed by the compressive force of an electric field. He then derived equations from which Young's modulus (E) and the electric breakdown voltage (V_{cr}) can be calculated. I believe Crowley's work to be generally correct and potentially useful. However, he apparently was not aware of a body of literature directly related to his study and consequently ignored some important details. The purpose of this letter is to augment his discussion. I would like to (*a*) comment on the assumption of elasticity, (*b*) discuss calculations of Young's modulus from measurements of changes in capacitance induced by electric fields, and (*c*) discuss additional phenomena which can cause electrical breakdown of thin lipid films.

Crowley indirectly raised the question of whether or not the bilayer film can be treated as an elastic system. White and Thompson (1973) have shown that it can indeed be treated this way. If the membrane is elastic but incompressible (i.e. density = constant), then the volume of the bilayer film must remain constant when the film is deformed by the stress generated by an electric field. Thus, if the film becomes thinner, its area must increase to satisfy the relation

$$\delta_{m_0} A_{m_0} = \delta_{m_V} A_{m_V}, \qquad (1)$$

where δ_m is membrane thickness, A_m is area, and the subscripts 0 and V refer, respectively, to the values in the absence and presence of a potential. The specific capacitance C_m of a bilayer film can be determined by measuring the film's total capacitance C_T and area A_m using the equation

$$C_m = C_T / A_m. \qquad (2)$$

Methods for performing these measurements with high precision and accuracy have been described by White (1970 *b*) and White and Thompson (1973). C_m depends primarily upon the thickness (δ_m) and the dielectric coefficient (ϵ_m) of the hydrocarbon interior and can be calculated from the parallel plate capacitor formula (Hanai et al., 1964)

$$C_m = \epsilon_0 \epsilon_m / \delta_m, \qquad (3)$$

where $\epsilon_0 = 8.85 \times 10^{-12}$ F/meter. The application of a potential V causes C_T, C_m, *and* A_m to increase (White and Thompson, 1973). It is easy to show using Eqs. 1–3 that

$$C_{m_0} / C_{m_V} = A_{m_0} / A_{m_V} \qquad (4)$$

and

$$C_{T_0}/C_{T_V} = C_{m_0}^2/C_{m_V}^2, \tag{5}$$

providing the density and dielectric coefficient of the film remain constant. White and Thompson (1973) have shown these relations to hold true to within 5% for bisdihydrosterculoyl phosphatidylcholine films. It therefore appears reasonable to conclude that the film behaves as an elastic layer of constant density.

The above conclusion has an important implication: when the film is deformed its thickness decreases, its area increases, and consequently the area per surfactant molecule in the interfaces *must* increase. If the total number of surfactant molecules remains constant, it follows that

$$A_V = (\delta_{m_0}/\delta_{m_V})A_0, \tag{6}$$

where A_V and A_0 are the areas per surfactant molecule at one interface in the presence and absence of the potential. Andrews et al. (1970) have reported $A_0 = 40$ Å^2, $\delta_{m_0} = 48$ Å, and $\delta_{m_V} = 45$ Å for glycerol monooleate-decane films in 0.1 M NaCl when the potential is about 100 mV. Therefore $A_V \simeq 42.5$ Å^2 from Eq. 6. It would appear at first that this should cause the surface pressure of the surfactant molecules to decrease or, equivalently, the interfacial tension to *increase*. We believe, however, that interfacial tension or, equivalently, the interfacial free energy *decreases* when an electric field is applied (White, 1970 *b*; Andrews et al., 1970). This would mean that the surface pressure of the surfactant molecules must actually increase even though the area per molecule has increased. The anomalous increase in surface pressure can be readily explained by assuming the interdigitation of the surfactant alkyl chains increases in the film's interior as proposed by Taylor and Haydon (1966). This increase in surface pressure implies that the interfacial free energy must decrease. Why does this favorable decrease in free energy not lead to further interdigitation? The answer must be that the increase in area per surfactant molecule exposes more solute and solvent alkyl chains to the aqueous phases. This exposure is not energetically favorable to further increases in the area per molecule. The hypothetical structure of a film before and after the application of a voltage is shown schematically in Fig. 1. One can imagine that as the voltage across a thin film is increased, a point is reached where the increased interfacial free energy due to increased alkyl chain-water interactions can no longer be compensated for by the increase in interfacial pressure caused by interdigitation. At this point the film might break

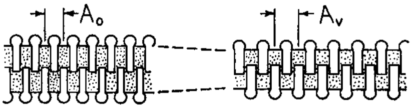

FIGURE 1 Schematic representation of the structural changes in a bilayer film caused by an electric field induced stress. The bilayer is assumed to be elastic but incompressible (i.e., density = constant). When the film thins its area must increase. Consequently, if the number of surfactant molecules is constant, the area per surfactant molecule must increase from A_0 to A_V. This increase in area suggests that the interfacial free energy per unit area should increase but in fact it decreases. The decrease probably results from an increase in surface pressure due to interdigitation of the alkyl chains of the surfactant molecules. In the figure, a change is shown in the shape of the surfactant molecule when the film is deformed. Such a change is consistent with the work of Andrews et al. (1970). The stippled areas represent the volume occupied by solvent molecules.

into small surfactant-solvent droplets with a more favorable interfacial free energy. The above discussion is of course very qualitative. Whether or not it is a reasonable picture must await further developments in theory and experiment. However, the bilayer film appears to be a reasonably complex interfacial structure and nonspecific mechanisms for electric breakdown such as Crowley (1973) presented may be inappropriate.

Crowley (1973) mentions the difficulty of obtaining good data for the calculation of Young's modulus and resorts to order of magnitude calculations. Actually, excellent data for reasonably accurate calculations exist in the literature (White, 1970 *a*, *b*; Andrews et al., 1970; Fettiplace et al., 1971). White (1970 *a*) and White and Thompson (1973) have shown that the specific capacitance of bilayer films obeys within experimental error the relation

$$C_{m_V} = C_{m_0} + \beta V^2, \tag{7}$$

provided $V \leq 100$ mV. β is a constant. A similar equation has been derived by White and Thompson (1973) who assumed the film to be elastic and the changes in thickness to be small. They found

$$C_{m_0} = \epsilon_0 \epsilon_m / \delta_{m_0} \tag{8}$$

and

$$\beta = (1/E)(\epsilon_0^2 \epsilon_m^2 / [2\delta^3_{m_0}]), \tag{9}$$

where E is Young's modulus. Eq. 9 is approximate and was found not to be entirely consistent with experiment. However, it is adequate for the purpose of estimating E. Data available in the literature have been used to calculate E from Eq. 9 for several bilayer films. The results, summarized in Table I, show that Crowley's order of magnitude calculations are quite good. One point should be noted however. Crowley used the data of Rosen and Sutton (1968) to determine the percent change in *specific* capacitance with applied potential. Unfortunately, the data of Rosen and Sutton are actually expressed as percent change in *total*

TABLE I

RESULTS OF CALCULATIONS OF YOUNG'S MODULUS (E) FROM DATA IN THE LITERATURE USING EQ. 9

The results are in good agreement with those of Crowley (1973). All measurements were performed at 20°C.

Membrane composition	ϵ_m	δ_{m_0}	$\beta \frac{(f/m^2)^*}{V^2}$	E	Reference
		nm		*dyn/cm²*	
Phosphatidylcholine‡ in *n*-decane	2.1	4.65	4.96×10^{-2}	3.46×10^{6}	White and Thompson (1973)
Glycerol monooleate in *n*-decane	2.1	4.8	3.67×10^{-2}	4.16×10^{5}	Andrews et al. (1970)
Oxidized cholesterol in *n*-decane	2.24	3.5	1.23×10^{-2}	3.72×10^{6}	White (1970 *a*)

* From Eq. 7.

‡ bisdihydrosterculoyl phosphatidylcholine.

capacitance which includes changes in area as well as changes in specific capacitance. It can be shown with the aid of Eq. 4 and the relations $\Delta C_T = C_{TV} - C_{T_0}$ and $\Delta C_m = C_{mV} - C_{m_0}$ that

$$\Delta C_T / C_{T_0} = 2(\Delta C_m / C_{m_0}) + (\Delta C_m / C_{m_0})^2. \tag{10}$$

It is clear that the fractional change in total capacitance is at least twice that of the specific capacitance. Another fact must be considered if changes in total capacitance are to be used to determine Young's modulus. Namely, the area of the bilayer can change in unpredictable ways during the course of an experiment due to changes in the amount of bulk lipid solution in the annulus surrounding the thin film (White, 1972; White and Thompson, 1973). The changes in annulus volume are due to leakage or recruitment of bulk solution to or from the surface of the partition containing the aperture. Thus, A_m can be difficult to control and it is best to measure changes in C_m rather than C_T.

Finally, Crowley assumes that electric breakdown is attributable only to instabilities in the bilayer per se. This assumption is not necessarily a good one unless the dimensions of the aperture supporting the annulus and film have been carefully controlled. White (1972) has performed a complete analysis of the annulus surrounding the bilayer and has shown that the stability of the annulus-bilayer system depends upon the geometry of the aperture. Briefly, if the ratio of aperture length (i.e. partition thickness) to aperture diameter is too small, the application of a potential can cause the shape of the annulus to change drastically and suddenly, resulting in film breakage. Breakage from this cause is obviously unrelated to instabilities in the film itself. Such breakage can be avoided by making sure the ratio of aperture length to diameter is sufficiently large (White, 1972).

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