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Nonequilibrium Thermodynamic Studies on Membrane Phenomena. Transport of Electrolytic Solutions through Progesterone Plug Membrane

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Studies on hydrodynamic and electroosmotic permeation of water and aqueous solutions of NaCl, KCl, and $MgCl_2$ across progesterone plug membrane have been carried out to characterize the electrical nature of progesterone interfaces. Electrophoretic mobilities of progesterone particles dispersed in these aqueous solutions have also been measured. Experiments were confined to the range where linear flux/force relationships hold. Membrane parameters have been evaluated with the data obtained and the membrane/solution electrical interface has been explained using electrical double layer model and theory of nonequilibrium thermodynamics. Zeta potentials have been evaluated from electroosmotic and electrophoretic flux data and their dependence on concentration examined.

A variety of transport phenomena is known to take place when a membrane system is subjected to various driving forces such as gradients of electric potential, concentration, and hydrostatic pressure. The phenomenon of mass transmission through natural membranes is very complex[1] having immense physiological and medicinal applications.[2] In view of the complexities of these membranes considerable interest has developed in the study of transport behavior through model membranes.[3] It has been found that these model membranes possess certain dimensional, electrical permeability, and excitability characteristics that closely resemble the behavior of natural membranes.[4] Recently we have made extensive studies on the application of nonequilibrium thermodynamics to the transport phenomenon across testosterone plug membrane[5–7] (model membrane).

This paper is concerned with the study of the transport properties of an isothermal system consisting of a progesterone plug membrane, water, and aqueous solutions of NaCl, KCl, and $MgCl_2$ in the concentration range of 10^{-4} to 10^{-3} $mol\,l^{-1}$ on the basis of nonequilibrium thermodynamics. Such studies with respect to progesterone interfaces in various types of electrolytic solutions are expected to throw light on various facets of its functions.[8] For this purpose measurements on hydrodynamic permeability, electroosmosis and electrophoresis have been carried out on progesterone/aqueous electrolyte systems and the data so obtained have been analysed in the light of nonequilibrium thermodynamic theories with a view to ascertaining the form of transport equation and evaluating the phenomenological coefficients.

Experimental

(a) Materials: Progesterone obtained from Sigma Chemical Company (Saint Louis, USA) was used as such to prepare the membrane plug. Analytical grade NaCl, KCl, and $MgCl_2$ obtained from BDH, India were used to prepare their aqueous solutions in distilled water (specific conductance of the order 10^{-6} S). Various solutions of $MgCl_2$ were prepared from its stock solution standardized by EDTA titration.

(b) Experimental Cell/Membrane-Plug Assembly and Silver-Silver Chloride Electrodes: A known amount of progesterone powder was mixed with a small amount of araldite which was then cast in the form of a plug, in a Pyrex glass cell having a constriction in the middle by mechanical compression as described elsewhere.[9] The thickness of the membrane was 5.02 mm and the area of the surface was nearly 3.24×10^{-4} m^2. Reversible silver–silver chloride electrodes were prepared by anodic deposition of chloride ions on a silver disc attached with a silver rod, from 0.1 M NaCl solution (1 M=1 $mol\,dm^{-3}$) at 0.4 $mA\,cm^{-2}$. It was found that anodically formed chloride layer on silver was very thin.

(c) Measurement of Electroosmotic Permeabilities: The experimental cell was filled with the permeants under investigation and left for 24 h for equilibration. The cell was subsequently filled with degassed fresh permeant to ensure that the concentration of experimental solution remained the same as compounded before equilibration. An electronically operated power supply (HIL, India) was used to apply potential gradients upto 50 V employing Ag-AgCl electrodes. The electrodes were adjusted to cover the maximum surface area of the plug from both the sides.

The volumetric flux was measured by following the rate of displacement of solution/air meniscus in a horizontally placed graduated capillary tube of cross sectional area 1.484×10^{-6} m^2. The electroosmotic flux was found to take place from negative to positive electrode.

The hydrodynamic permeability was measured with the same cell as used for electroosmosis. A constant hydrostatic pressure difference was maintained across the membrane by a constant pressure head device and the volume flow was calculated from the movement of solution/air meniscus in the horizontally placed graduated capillary attached to the cell. The difference of the pressure on the two surfaces of the membrane was measured to ± 0.001 cm with a cathetometer.

It was observed that the flow of solution takes place in the measuring capillary even when pressure difference and potential difference on both sides of the plug membrane is zero. This residual flow arises due to capillary active forces operating at the solution/air interface in the measuring capillary tube. The data given in these measurements have been corrected for this residual flow.

(d) Conductance of Membrane Equilibrated with Permeants: Conductance of membrane equilibrated with various solutions were measured with a conductivity bridge (Toshniwal, India) at 50 Hz. Conductances of the permeants were measured before and after electroosmosis with the same apparatus.

(e) Measurement of Electrophoretic Velocities: The electrophoretic velocities of progesterone particles dispersed in the aqueous solutions were measured by the method described elsewhere.[10] Corrections were made for the downward movement due to the action of gravitational forces. Movement of the boundary was from anode to cathode. Measurements of electroosmotic permeability and electrophoretic velocities for a particular system were repeated several times. The deviation from the average value was always less than 5% showing that the measurements are fairly reproducible.

All the measurements were carried out in an air thermostat maintained at 25±0.5 °C.

Results and Discussion

According to nonequilibrium thermodynamics, the isothermal volume flux J_v and the electric current I, through a permeant-equilibrated membrane under the simultaneous action of a hydrodynamic pressure difference ΔP and an electric potential difference $\Delta\Phi$, are given by[11,12]

$$J_v = L_{11}\left(\frac{\Delta P}{T}\right) + L_{12}\left(\frac{\Delta\Phi}{T}\right) \tag{1}$$

$$I = L_{21}\left(\frac{\Delta P}{T}\right) + L_{22}\left(\frac{\Delta\Phi}{T}\right) \tag{2}$$

The parameters L_{ij} $(i, j=1, 2)$ are called phenomenological coefficients. We restrict ourselves to the examination of the applicability of Eq. 1 only. This equation predicts a linear relationship between $(J_v)_{\Delta\Phi=0}$ and ΔP with the slope yielding the value of hydrodynamic transport coefficient L_{11}/T. A linear relationship was also observed between the electroosmotic volume flux $(J_v)_{\Delta P=0}$ and $\Delta\Phi$, whose slope yielded the value of L_{12}/T. L_{22}/T, the conductance of membrane equilibrated with permeant was directly noted by conductivity bridge.

Further the classical theory[13] of electrical double layer reveals that for a plug membrane consisting of an array of n parallel capillaries and equivalent pore radius r, the transport coefficients are given by:

$$\frac{L_{11}}{T} = \frac{n\pi r^4}{8\eta l} \tag{3}$$

$$\frac{L_{12}}{T} = \frac{n\varepsilon r^2}{4\eta l}\cdot\zeta_{\text{e.o.}} \tag{4}$$

$$\frac{L_{22}}{T} = \frac{n\pi r^2}{l}\cdot\kappa \tag{5}$$

where η is the coefficient of viscosity of the permeating solutions, l is the average length of membrane capillaries, $\zeta_{\text{e.o.}}$ is the zeta potential causing electroosmosis and κ is the specific conductance of the permeant. Values of these transport coefficients are recorded in Table 1.

The electroosmotic flow was found to occur towards positive electrode. This behavior may be explained on the basis of the electrical double layer formed at the membrane permeant interface. The oxygen atom of $>$C=O groups at C-3 and C-20 and electron density around the olefinic bond is collectively responsible for generating overall negative charge at the progesterone molecules present in the membrane matrix. The cations and anions present in the solution are hydrated and move with the same linear velocity as respective ions.[14] Water dipoles present in the permeating solution get preferentially adsorbed at the negatively charged matrix oriented with their positive ends towards the membrane surface and form the inner Helmholtz plane (IHP). The hydrated cations are attracted towards the negative part of water dipoles forming outer Helmholtz plane (OHP). The diffusely dispersed part of the electrical double layer (Fig. 1) has an excess of hydrated chloride ions with the result that electroosmotic transport would occur towards the anode in accordance with our observation.

Electrophoresis. Electrophoretic migration of progesterone particles dispersed in these electrolytic solutions occur towards the cathode. The following linear relationship holds between the electrophoretic velocity $(V_e)_{g=0}$ and applied potential difference $\Delta\Phi$ as found earlier.[5]

$$(V_e)_{g=0} = \frac{L_{12}^*}{T}\cdot\Delta\Phi \tag{6}$$

Table 1. Phenomenological Coefficients for Progesterone/Aqueous Electrolyte Solution Systems

$C\times10^4$	$\frac{L_{11}}{T}\times10^{13}$			$\frac{L_{12}}{T}\times10^{12}$			$\frac{L_{22}}{T}\times10^{6}$			$\frac{L_{12}^*}{T}\times10^{8}$		
mol l^{-1}	$\text{m}^5\,\text{S}^{-1}\,\text{N}^{-1}$			$\text{m}^3\,\text{S}^{-1}\,\text{V}^{-1}$			S			$\text{mS}^{-1}\,\text{V}^{-1}$		
	NaCl	KCl	$MgCl_2$	NaCl	KCl	$MgCl_2$	NaCl	KCl	$MgCl_2$	NaCl	KCl	$MgCl_2$
0.0	8.01	8.10	8.04	2.90	2.92	2.92	0.20	0.20	0.19	17.8	17.7	17.8
1.0	8.20	8.42	8.35	3.12	3.30	3.04	0.24	0.31	0.29	19.4	19.9	18.8
2.0	8.52	8.80	8.72	3.30	3.52	3.20	0.41	0.54	0.58	20.0	20.6	18.9
4.0	9.31	9.64	9.25	3.54	3.91	3.35	0.86	1.06	1.14	21.2	21.4	19.6
6.0	11.02	9.60	21.80	3.92	4.40	3.48	1.35	1.74	9.94	21.8	21.9	21.0
10.0	11.88	13.80	10.10	4.38	5.42	3.80	2.42	3.23	2.95	24.8	22.7	22.3

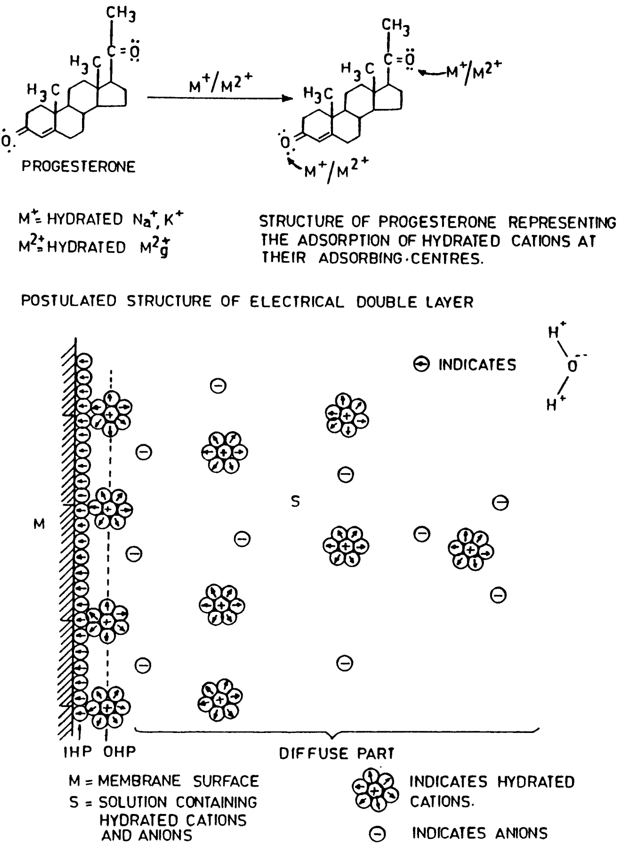

Fig. 1.

where

$$\frac{L_{12}^*}{T} = \frac{\varepsilon \zeta_{\text{e.p.}}}{4\pi\eta l'} \tag{7}$$

L_{12}^*/T is the electrophoretic transport coefficient, ε and η are the dielectric constant and viscosity of the solution, respectively. $\zeta_{\text{e.p.}}$ is the zeta potential and l' is the distance between the two electrodes of the electrophoretic cell.

The values of L_{12}^*/T obtained from the slope of linear plots of $(V_e)_{g=0}$ vs. $\Delta\Phi$ are recorded in Table 1.

The preferential adsorption of hydrated cations at the surface of progesterone particles cause it to have net positive charge. This facilitates the electrophoretic migration towards cathode.

Membrane Parameters/Characterization of Membrane Structure. The extent of flow and nature of flow through a membrane is determined to a great extent by the characteristics of membrane itself. Hence, certain important parameters which provide an insight into the structural details viz., (i) average pore radii and average number of pores, (ii) zeta potential have been determined using fluid permeation measurements e.g., electroosmosis and hydrodynamic permeation, conductance of the membrane equilibrated with permeants. The average pore radii r and average number of pores n, have been evaluated using the equations[5]

$$r = \left[\frac{8\eta\kappa L_{11}/T}{L_{22}/T}\right]^{1/2} \tag{8}$$

and

$$n = \frac{\frac{L_{22}}{T} \times l}{\pi r^2 \kappa} . \tag{9}$$

The values of these parameters are recorded in Table 2.

Evaluation of Zeta-Potentials: Electrokinetic phenomena are only directly related to the nature of the mobile part of the electric double layer and may, therefore, only be interpreted in terms of potential (zeta) or the charge density at the surface of shear. No direct information is given about the charge density at the surface of the membrane. Zeta potentials have been calculated using the following equations[5]

$$\zeta_{\text{e.o.}} = \frac{4\pi\eta\kappa}{\varepsilon\left(\frac{L_{22}}{T}\right)} \times \left(\frac{L_{12}}{T}\right)_{\text{e.o.}} \times 9 \times 10^4 \text{ V} \tag{10}$$

and

$$\zeta_{\text{e.p.}} = \frac{4\pi\eta l'}{\varepsilon} \times \frac{L_{12}^*}{T} \times 9 \times 10^4 \text{ V} \tag{11}$$

where $\zeta_{\text{e.o.}}$ and $\zeta_{\text{e.p.}}$ are the zeta potentials calculated using electroosmotic and electrophoretic transport coefficients respectively. There are instances where the above relationships are not applicable due to complicating effects arising on account of double layer polarization.[15]

It is evident from Table 2 that the zeta potentials calculated from electroosmotic and electrophoretic data are not comparable, which observation is consistent with our earlier findings.[5,7]

The discrepancy in the two values of zeta potentials

Table 2. Membrane Parameters for Progesterone/Aqueous Electrolyte Systems[a]

$C\times10^4$	$r\times10^6$			$n\times10^3$			$\zeta_{\text{e.o.}}\times10^3$			$\zeta_{\text{e.p.}}\times10^3$		
	m						V			V		
mol l^{-1}	NaCl	KCl	MgCl$_2$	NaCl	KCl	MgCl$_2$	NaCl	KCl	MgCl$_2$	NaCl	KCl	MgCl$_2$
1.0	6.66	6.65	6.68	4.80	5.46	5.27	31.7	32.1	29.5	43.3	44.3	41.5
2.0	6.70	6.64	6.65	6.09	4.66	5.71	32.2	32.9	30.1	44.5	45.9	42.4
4.0	6.82	6.71	6.77	5.46	6.03	5.82	32.5	33.7	30.6	45.7	47.5	43.1
6.0	6.72	6.81	6.81	6.22	6.48	6.06	32.7	34.2	31.0	46.3	48.4	43.5
10.0	6.97	6.01	6.72	6.49	6.11	6.84	33.0	34.8	31.4	47.2	49.7	44.0

a) Average pore radii r, average no. of pores n, and zeta potentials $\zeta_{\text{e.o.}}$ and $\zeta_{\text{e.p.}}$.

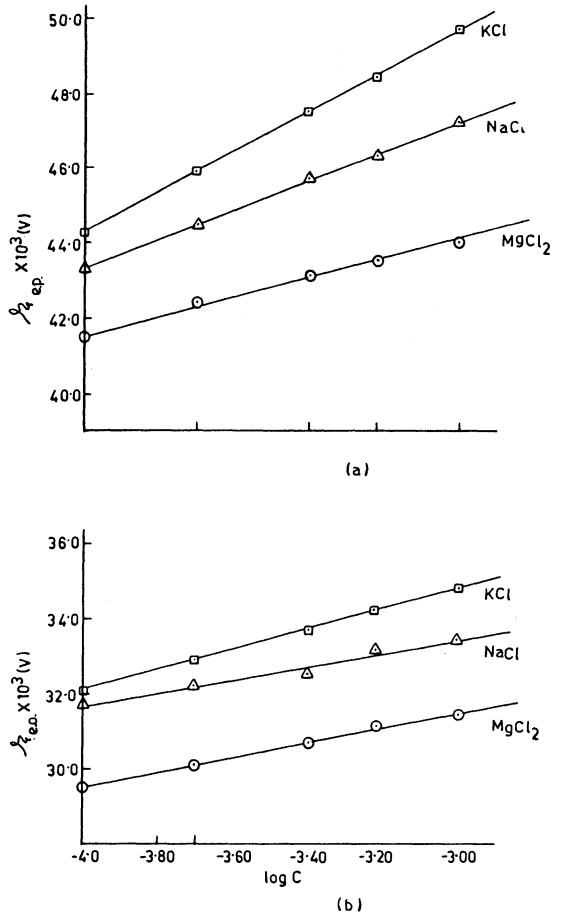

Fig. 2. Dependence of zeta potential (ζ) on log$C$ for progesterone/aq electrolyte solution systems (concn 10^{-3} mol l^{-1}).

is attributable to: i) change in the electrokinetic behavior owing to the decrease in particle size for electrophoretic measurements, ii) change in the hydrodynamic environment in the two cases, and iii) variation of the dielectric constant ε and the viscosity η in the double layer. It is not possible to calculate these quantities directly within the double layer. Therefore, no definite conclusion could be drawn.[16]

Zeta potentials vary nonlinearly with concentration of solutions while its dependence with log C is found to be linear (Fig. 2) and the following equation[5] holds good.

$$\zeta = A + B \log C \qquad (20)$$

where A is taken as approximately constant for conditions under which the charge on the membrane surface does not change sign and B is another constant. The existence of positive zeta potentials may be attributed to the firm attachment of cations at the surface of capillary channels of the membrane.

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