

## LETTERS TO THE EDITOR

### Membrane Dipole Potentials

Dear Sir:

It is commonly assumed that a biological membrane is a simple dielectric, i.e., that the electrical potential difference across it,  $V$ , is proportional to the charge on its surfaces,  $\pm Q$ :

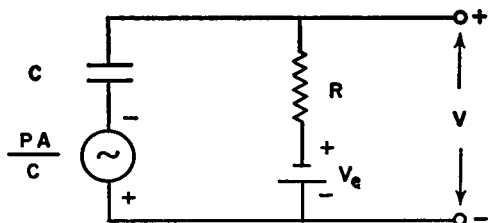
$$V = 4\pi LQ/\epsilon A = Q/C, \quad (1)$$

where  $L$  is the membrane thickness,  $\epsilon$  the dielectric constant,  $A$  the area, and  $C = \epsilon A/4\pi L$  the capacitance.

This is not true if molecules with permanent electric dipole moments are embedded in the membrane, for then part of the volume polarization is independent of the macroscopic electric field.<sup>1</sup> If the component of this part of the polarization normal to the surface of the membrane is  $P$  (positive in the direction  $+Q$  to  $-Q$ ), then<sup>2</sup>

$$V = 4\pi LQ/\epsilon A - 4\pi LP/\epsilon = (Q - PA)/C. \quad (2)$$

In the usual case a membrane of high specific resistance separates two solutions of low specific resistance. The equilibrium or steady-state electrical potential difference,  $V_e$ , is determined solely by the chemical potentials of the ions in the solutions (those to which the membrane is permeable) and by their transport numbers (3, 4). If ions are able to move from one side of the membrane to the other through a resistive pathway of resistance  $R$ , the system is electrically equivalent to the following circuit:



A zero-impedance voltage source  $PA/C$  appears in series with the capacitor. The ion flux changes the charge on the capacitor,  $Q$ , and the potential across it,  $Q/C$ , but it does not change  $P$ .

If  $P$  is constant,  $V$  approaches  $V_e$  exponentially with the time constant  $RC$ , just as in the case of the simple dielectric, but  $Q$  approaches  $CV_e + PA$  rather than  $CV_e$  (5).

If  $P$  changes gradually, the membrane behaves like a wax electret (6). Adams (7) and Swann (2, 8) have discussed this case for the exponential decay  $P = P_0 \exp(-t/\tau)$ , where  $P_0$  is the initial polarization,  $t$  is the time, and  $\tau$  is a decay constant. In the limit  $\tau \gg RC$ , the potential changes exponentially with the time constant  $RC$  from its initial value (whatever it

<sup>1</sup> See the discussion of electric fields in matter given by Purcell (1).

<sup>2</sup> If there are  $n$  molecules per unit volume with surface-normal dipole moments  $p$ ,  $P = np$ . If the polarization is not uniform,  $P$  is the value averaged over the thickness of the membrane (reference 2).

may be) to the value  $V_s + P_0AR/\tau$ , and then it decays back to  $V_s$  with the time constant  $\tau$ . The voltage offset  $P_0AR/\tau$  is large only if the membrane is thick and has a high specific resistance.

Beament (9) has generated offsets as large as 4 v by using an external battery to polarize a  $0.25 \mu$  coating of grease on the cuticle of the cockroach *Periplaneta* ( $\tau = 1.2 \times 10^3$  sec,  $RC = 10^2$  sec). The results of these "over-charge" experiments are consistent with the electret theory if  $P_0$  is of order 20 statcoulomb/cm<sup>2</sup>, a value which is not unreasonable.

If  $P$  changes rapidly, so rapidly that the transient is complete in a time short compared to  $RC$ , the membrane potential follows the change in polarization, since  $Q$  remains constant during this period of time. High-frequency components of  $P$  appear at the output of the equivalent circuit without appreciable attenuation or change in phase. Therefore, if some mechanism exists for driving  $P$ , the membrane can generate signals at a frequency large compared to  $1/2\pi RC$ .<sup>1</sup>

An example is the early receptor potential of the eye observed in intraretinal recordings by Brown and Murakami (11) and in the electroretinogram by Cone (12). Rhodopsin is known to be a major component of the membranes of the outer segment of the photoreceptors, to be packed in an ordered fashion, and to undergo rapid isomerizations triggered by the absorption of light. If the isomerizations change the component of the electric dipole moment of the rhodopsin molecule normal to the plane of the membrane, then potential changes will be generated. If  $P$  changes suddenly by an amount  $\delta P$ , the potential will jump by an amount  $\delta V = -\delta PA/C$ , and then it will decay back to its equilibrium or steady-state value exponentially with the time constant  $RC$ . If  $N$  photons are absorbed by area  $A$  of membrane and each changes the surface-normal dipole moment of a rhodopsin molecule by an amount  $\delta p$ ,  $\delta V = -\delta pN/LC$ . For  $\delta p = 1$  Debye,  $N = 10^{13}$ ,  $L = 10^{-6}$  cm, and  $C = 1 \mu F$ , the potential jump is 3.3 mv. The experimental evidence for a mechanism of this kind is now substantial (13, 14). My purpose here is to point out how the problem can be stated in terms of elementary electric theory and to show how early receptor potentials are related to potentials generated by certain electrets.

This work was supported in part by USPHS Grant GM14423. Discussions with Alec Bangham, J. W. L. Beament, and R. A. Cone are gratefully acknowledged.

Received for publication 15 March 1968 and in revised form 4 June 1968.

HOWARD C. BERG  
Department of Biochemistry and  
Molecular Biology  
Harvard University  
Cambridge, Massachusetts 02138

## REFERENCES

1. PURCELL, E. M. 1965. Electricity and Magnetism. McGraw-Hill Book Co., New York. Chapter 9.
2. SWANN, W. F. G. 1950. *J. Franklin Inst.* 250:219.
3. CRAXFORD, S. R., O. GATTY, and ROTHSCILD. 1938. *Nature*. 141:1098.

<sup>1</sup> The only other way this can be done is to modulate  $C$ , e.g., by stretching the membrane (changing  $L$  and  $A$ ); see Katz (10).

4. DEAN, R. B., O. GATTY, and E. K. RIDEAL. 1940. *Trans. Faraday Soc.* **36**:161.
5. HEAVISIDE, O. 1892. *Electrical Papers*. Macmillan and Co., London, England. Vol. 1, p. 493.
6. EGUCHI, M. 1925. *Phil. Mag. Sixth Ser.* **49**:178.
7. ADAMS, E. P. 1927. *J. Franklin Inst.* **204**:469.
8. SWANN, W. F. G. 1953. *J. Franklin Inst.* **255**:513; **256**:167.
9. BEAMENT, J. W. L. 1961. *Nature*. **191**:217.
10. KATZ, B. 1950. *J. Physiol. (London)*. **111**:261.
11. BROWN, K. T., and M. MURAKAMI. 1964. *Nature*. **201**:626.
12. CONE, R. A. 1964. *Nature*. **204**:736.
13. CONE, R. A. 1967. *Science*. **155**:1128.
14. HAGINS, W. A., and R. E. MCGAUGHY. 1968. *Science*. **159**:213.