Biophys. Struct. Mechanism 2, 333–336 (1977)

Biophysics of Structure and Mechanism

© Springer-Verlag 1977

Quantitative Model for the Electric Response of Invertebrate and Vertebrate Photoreceptors*

L. Kramer and T. Widmann

Physik-Department der Technischen Universität München,
James-Franck-Straße, D-8046 Garching b. München,
Federal Republic of Germany

Abstract. We propose that the same mechanism which leads to light-adaptation in invertebrate photoreceptors is responsible for the excitation of the receptor potential in vertebrates. Several qualitative and quantitative features of the vertebrate receptor response support this hypothesis.

Key words: Photoreceptor model – Receptor potential – Vertebrate – Invertebrate – Adaptation.

We wish to describe an instructive procedure by which a recently proposed model for the quantitative interpretation of invertebrate photoreceptor potentials (Kramer, 1975; hereafter referred to as I) can be transformed into a model for the photoelectric response of vertebrate photoreceptors. The main postulates of the *invertebrate* model are as follows:

a1) There exist two types of channels K_1 and K_2 in the cell membrane with reversal potentials $E_1 \approx 10$ mV and $E_2 \approx -60$ mV. The "dark-channels" K_2 are unaffected by light.

b1) In darkness the "light-channels" K_2 are closed. Absorption of single photons leads via an unknown chain of events to a transient activation of many light-channels ("bumps"). The necessary amplification process is treated mathematically as a saturating chain reaction although other treatments or interpretations seem possible. Determination of this process remains of central importance. The single-photon events add up to give the total activation of light-channels described by an "activation-factor" x_A (= fraction of open light-channels).

c1) The average amplification inherent in single-photon events is assumed to be variable and characteristic for the adaptational state of the membrane as described by an "adaptation-factor" A ("bump-adaptation"). Thus in a light-adapted state ($A < 1$) the chain reactions are assumed to saturate earlier, leading to a smaller and

---

* Presented at the EMBO-Workshop on Transduction Mechanism of Photoreceptors, Jülich, October 4–8, 1976

somewhat faster response than in the dark-adapted state ($A = 1$). The process of light- and dark-adaptation is described in terms of simple kinetic equations. Generalizing those used in ref. I to allow for the sensitivity to recover in a rapid and a slow phase we take

$$A = \exp(-u) \tag{1}$$

$$\dot{u} = p_1 x_A/(1 + \beta p_1 x_A) - p_2 u + p_{-2} v \tag{2}$$

$$\dot{v} = p_2 u - (p_{-2} + p_3) v \tag{3}$$

with $p_3 \ll p_2$ (Eqs. (2), (3) reduce to Eq. (29) of ref. I for $p_{-2} = 0$). Good agreement with measurements on the recovery of sensitivity in *Limulus* (Benolken, 1962) during the first minutes of dark-adaptation is achieved in this way.

There exists considerable evidence that calcium, which probably enters the cell during light-activation, acts as an agent for light-adaptation (Brown, 1976). So u might be proportional to the intracellular calcium concentration. In ref. I it is demonstrated that the reduction in light-adaptation, which occurs when external calcium is reduced (Stieve and Wirth, 1971) can be simulated convincingly by the model.

It has been proposed that in *vertebrate* photoreceptors, where the light-response is hyperpolarizing instead of depolarizing, calcium acts as a transmitter in the chain of events which leads from absorption of photons in the disc region to a conductance decrease of the cell membrane (Hagins, 1972). Since light-adaptation in invertebrates is also a conductance-decreasing process it seems quite natural to connect the excitatory process in vertebrates with the adaptive process in invertebrates. In order to obtain a model for the vertebrate response which incorporates this idea, we have transformed the postulates b1) and c1) of the invertebrate model as follows:

b2) Similar discrete, amplifying activation events as in invertebrates take place at the cell membrane of the photoreceptor outer segment. They are, however, not triggered by photon absorption but occur spontaneously at a fixed rate P. The situation could thus be similar to that encountered in some invertebrates under conditions of "prolonged depolarizing afterpotential" (Minke et al., 1973).

c2) Absorption of photons leads to a reduction of the average amplification of the activation events as described by the quantity A ("bump-adaptation"), and therefore to a hyperpolarizing response.

The simplest version of the vertebrate model is obtained by replacing x_A by x_B in Equation (2) and replacing Equation (22) of ref. I by

$$\dot{x}_B = -k_1 x_B + \sigma I\,. \tag{4}$$

Also, in Equation (23) of ref. I the rate $k_1 X_1$ is replaced by P. Receptor potentials calculated with the resulting equations do not exhibit a transient minimum for long light stimuli in accord with measurements on isolated retinas of frog (Sickel, 1972) and gecko (Pinto and Pak, 1974). In other preparations such as turtle cones and rods (Baylor et al., 1974; Schwartz, 1976) and also gecko eye-cup preparations (Pinto and Pak, 1974) a transient minimum does exist. Following Baylor et al. (1974) one can include this feature by adding an ionic channel with time-delayed voltage-dependent conductance.

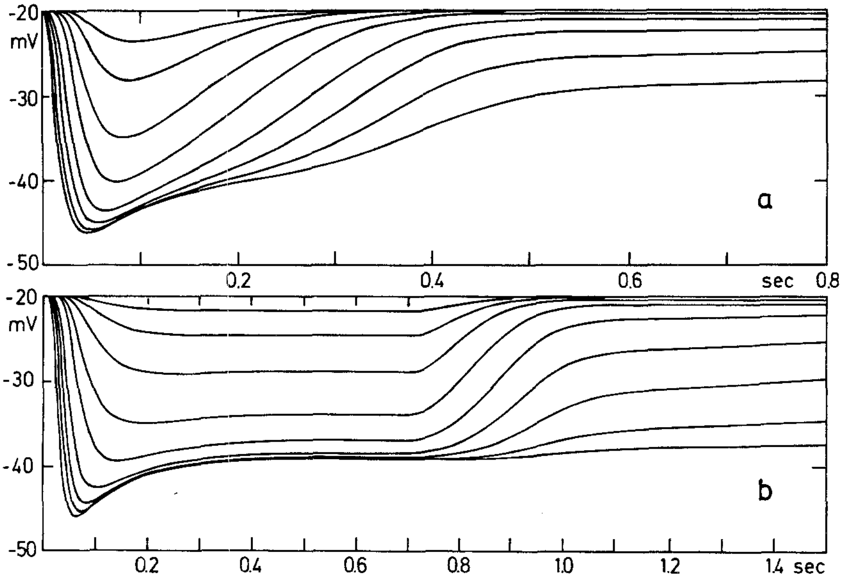

Fig. 1. Model response for $N = 100$, $k_0 = 150\ \mathrm{s}^{-1}$, $k_1 = p_2 = 20\ \mathrm{s}^{-1}$, $k_2 = 100\ \mathrm{s}^{-1}$, $p_{-2} = 0.05\ \mathrm{s}^{-1}$, $p_3 = 1\ \mathrm{s}^{-1}$, $\beta = 0$. a) Short light flash of duration Δt. Relative intensities: $\sigma I\,\Delta t = 1, 3, 10, 30, 10^2, 3 \times 10^2, 10^3, 3 \times 10^3$. b) Stimulus of 0.67 s duration. Relative intensities: $\sigma I = 3, 10, 30, 10^2, 3 \times 10^2, 10^3, 3 \times 10^3, 10^4, 3 \times 10^4\ \mathrm{s}^{-1}$

Although the resulting model responses exhibit quite satisfactory temporal behavior their amplitude is not sufficiently graded with intensity. We have removed this deficiency in a preliminary manner by replacing Equation (1) by $A = 1/(1 + u)$. The same goal can probably be achieved in a more satisfactory way by introducing an appropriate non-linearity into Equation (4). This then would indicate that transmitter release at the disc membrane also proceeds via (light-induced) amplification processes with variable amplification factor ("disc adaptation").

In Figure 1 the vertebrate model response for a particular set of parameters is shown for short and long stimuli of various intensity. For simplicity linear current-voltage relations for the channels K_1 and K_2 were taken. The curves agree satisfactorily with experimental results on turtle cones (Baylor et al., 1974; Figs. 5 and 6).

The model is consistent with the finding that in vertebrates dark-adaptation proceeds parallel with after-hyperpolarization (Baylor and Hodgkin, 1974). This phenomenon seems to form the basis of the concept of "equivalent background" established in psychophysical investigations (see e.g. Barlow, 1972). Introduction of the slow phase in the dark-adaptation of invertebrates [Eqs. (2), (3)] is essential for obtaining sufficiently long after-hyperpolarizations in vertebrates. In fact, for longer or stronger light stimuli even slower processes have to be added. The model is also consistent with the finding that in darkness there exist rather large voltage fluctuations which are reduced strongly by illumination (Simon et al., 1975).

In conclusion let us mention that the model as it stands is quite definitely not in its final form, but will need continuous improvement. In designing the model our aim is not just to obtain quantitative agreement with experiment, but to provide a framework from which to proceed towards an understanding of the underlying mechanisms. Thus we hope that, in spite of various deficiencies, the model reflects in some way the functional organization of photoreceptors. Moreover, the connection between vertebrates and invertebrates which we propose here could be correct even if the model should turn out to fail severely.

Acknowledgement. We wish to thank Professor Dr. H. Stieve for his interest and discussions of this work.

References

Barlow, H. B.: Dark and light adaptation: Psychophysics. In: Handbook of sensory physiology, vol. VII/4 (ed. D. Jameson, L. M. Hurvich), pp. 1—28. Berlin-Heidelberg-New York: Springer 1972

Baylor, D. A., Hodgkin, A. L.: Changes in time scale and sensitivity in turtle photoreceptors. J. Physiol. **242**, 729—758 (1974)

Baylor, D. A., Hodgkin, A. L., Lamb, T. D.: Reconstruction of the electrical responses of turtle cones to flashes and steps of light. J. Physiol. **242**, 759—791 (1974)

Benolken, R. M.: Effects of light- and dark-adaptation processes on the generator potential of the *Limulus* eye. Vision Res. **2**, 103—124 (1962)

Brown, J. E.: Calcium ion, a putative intracellular messenger for light-adaptation in *Limulus* ventral photoreceptors. Embo-workshop on transduction mechanism of photoreceptors, 4—8 October 1976, Jülich, Federal Republic of Germany

Hagins, W. A.: The visual process: Excitatory mechanisms in the primary receptor cells. Ann. Rev. Biophys. Bioeng. **1**, 131—158 (1972)

Kramer, L.: Interpretation of invertebrate photoreceptor potentials in terms of a quantitative model. Biophys. Struct. Mechanism **1**, 239—257 (1975)

Minke, B., Hochstein, S., Hillman, P.: Antagonistic process as source of visible-light suppression of afterpotential in *Limulus* UV photoreceptors. J. gen. Physiol. **62**, 787—791 (1973)

Pinto, L. H., Pak, W. L.: Light-induced changes in photoreceptor membrane resistance and potential in gecko retinas. J. gen. Physiol. **64**, 26—69 (1974)

Schwartz, E. A.: Electrical properties of the rod syncytium in the retina of the turtle. J. Physiol. **257**, 379—406 (1976)

Sickel, W.: Retinal metabolism in dark and light. In: Handbook of sensory physiology, vol. VII/2 (ed. M. G. F. Fuortes), pp. 667—727. Berlin-Heidelberg-New York: Springer 1972

Simon, E. J., Lamb, T. D., Hodgkin, A. L.: Spontaneous voltage fluctuations in retinal cones and bipolar cells. Nature (Lond.) **256**, 661—662 (1975)

Stieve, H., Wirth, C.: Über die Ionenabhängigkeit des Rezeptorpotentials der Retina von *Astacus leptodactylus*. Z. Naturforsch. **26b**, 457—470 (1971)

Received November 19, 1976