MASTER

THE RETINAL CONE RECEPTOR AS AN IDEAL LIGHT COLLECTOR

Roland Winston^{*}

The Enrico Fermi Institute and Department of Physics,
The University of Chicago, Chicago, Illinois 60637

And

Jay M. Enoch⁺

Department of Ophthalmology and Oscar Johnson
Institute, Washington University School of Medicine,
St. Louis, Missouri 63110

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

The Retinal Cone Receptor as an Ideal Light Collector

Roland Winston^{*}

The Enrico Fermi Institute and Department of Physics,
The University of Chicago, Chicago, Illinois 60637

And

Jay M. Enoch⁺

Department of Ophthalmology and Oscar Johnson
Institute, Washington University School of Medicine,
St. Louis, Missouri 63110

Index Headings: Geometrical Optics; Vision.

The purpose of this note is to point out a striking similarity between the ellipsoid portion of retinal cone receptors and the design of an ideal light collector,¹⁾ i.e. a non-imaging optical system with an f number = 0.5. This similarity suggests that it may be useful to formulate a simple geometrical optics model of the ellipsoid and discuss the directional acceptance properties of such a model in the hope of improving our understanding of mechanisms contributing to the directional sensitivity of the retina.

The theory of ideal light collectors²⁾ yields relations between the angular acceptance at the entrance aperture $\theta_{\max}$, the ratio of diameters of exit aperture to entrance aperture d_2/d_1 and the over-all length L (See Fig. 1). The pertinent formulae are

$$d_2/d_1 = \sin \theta_{\max} \quad (1)$$

and

$$L = (1/2) (d_1 + d_2) \cot \theta_{\max}. \quad (2)$$

It is well known that cone receptors in the retina are found in a variety of shapes³⁾ ranging from nearly cylindrical ($d_1 \sim d_2$) to highly tapered ($d_1 \sim 5 d_2$). From the viewpoint of light collection, it is the latter that are of most interest. Therefore, we consider this case in some detail. An example of a highly tapered cone cell is shown in Fig. 1, top⁴⁾. The ellipsoid portion is well represented by the ideal light collector shown in Fig. 1, bottom. In Figure 1, the diameters d_1 , d_2 of the collector correspond to the diameters of the inner and outer segments of the cone cell, while the length of the ellipsoid corresponds to the collector length L . To fit the ellipsoid shape, we have used $\theta_{\max} \sim 13^\circ$. This value is compatible with the numerical aperture of the retinal receptor (See Appendix, Ref. 3). In

addition, it is consistent with the maximum angle of incidence allowed by the limit of the human exit pupil.³⁾

The cone receptor differs from an ideal light collector in at least two significant respects. First, the boundary surface of the ideal collector is reflecting for all angles of incidence, while the boundary surface of the cone receptor which separates the inside medium with higher index of refraction n (inside) from the outside medium with lower index of refraction n (outside) is effective only by total internal reflection. Hence only rays in the angular range $\theta_c \leq \alpha \leq \pi/2$ are reflected efficiently where α is the angle of incidence with respect to the inward normal and θ_c is the critical angle. To see how this modifies the efficiency of an ideal light collector, Fig. 2 (curve B) shows the angular acceptance of the light collector for $\theta_c \approx 74^\circ$. This corresponds to $n(\text{inside})/n(\text{outside}) = 1.04$ which is within the range of values reported in the literature.⁵⁾ For the purposes of this model, it is assumed that homogeneity and isotropic properties exist in the light collector. The same figure (curve C) shows how the effective angular acceptance is modified by taking into account the fact that the probable orientation of the absorption axis of the photolabile pigment is perpendicular to the optic axis.⁶⁾ Of interest is the fact that curves B and C are quite similar, i.e., they only differ by about 20%. This suggests that pigment orientation in the receptor outer segment only influences receptor directionality in a limited manner. In curves B and C (Fig. 2) only energy delivered to the outer segment is considered. Treatment is not given to path length within the outer segment or the probability of propagation of energy to the cell terminations. Second, we have omitted discussing diffraction effects.⁷⁾

FOOTNOTES

- * Supported in part by the U. S. Atomic Energy Commission and the Alfred P. Sloan Foundation.
- + Supported in part by Research Grant No. EY 00204 and Career Development Award No. K3-15,138 of the National Eye Institute, N.I.H., Bethesda, Maryland.
- 1. H. Hinterberger and R. Winston, Rev. Sci. Instr. 37, 1094 (1966).
- 2. R. Winston, J. Opt. Soc. Am. 60, 245 (1970).
- 3. J. M. Enoch, J. Opt. Soc. Am. 53, 71 (1963).
- 4. J. M. Enoch, Appendix B in Fiber Optics, by N. S. Kapany (Academic Press, New York 1967).
- 5. R. Barer, J. Opt. Soc. Am. 47, 545 (1957).
- 6. P. Liebman, Ann. N.Y. Acad. Sci. 157, Article 1, 250-264 (1969).
- 7. Another phase of the problem of retinal directional sensitivity is treated in J.M. Enoch and J. Scandrett, Invest. Ophthal. 10, 3/1971.

Figure Captions

- Fig. 1 top. Schematic diagram of a cone receptor in the human retina taken from Ref. 4 (original in G. Walls). In this example the ellipsoid region is highly tapered with a ratio of inner segment to outer segment diameter ~ 4.5 .
- Fig. 1 bottom. Construction of an ideal light collector for the case $\theta_{\max} = 13^\circ$.
- Fig. 2. Angular acceptance of a $\theta_{\max} = 13^\circ$ light collector. Curve A shows the acceptance of an ideal collector having walls with perfect reflectivity at all angles of incidence. Curve B includes the effect of critical reflection at the walls, assuming a relative index of refraction $n(\text{inside})/n(\text{outside}) = 1.04$. Curve C shows how B is modified by assuming the orientation of the absorption axis of the photolabile pigment is perpendicular to the optic axis.