Human foveal far-field radiation pattern

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As part of another study, a remarkable record of a freshly excised, human central foveal far-field radiation pattern has been obtained. This pattern has been analyzed by microdensitometry. A possible relationship to the Stiles-Crawford effect of the first kind (directional sensitivity of the retina) has been considered.

Studies of retinal receptor optical properties performed on excised (and in a few cases in vivo) preparations revealed individual rods and cones to have narrow directional transmissivity. This directionality for both classes of receptors was far narrower than that which would have been predicted from psychophysical measurements of the Stiles-Crawford effect of the first kind. However, these observations were consistent with comparable studies made on glass fiber optics elements of comparable dimensions and difference in index of refraction (core and cladding). For example, see Fig. 17 in reference 3.

This discrepancy in findings was disturbing, and a means was sought to link or reconcile the two sets of findings. As visual response always reflects the summed action of many receptors, in order to evaluate the problem, some form of integrated estimate of receptor directionality (determined optically) was needed. Such a technique was described in a chapter written by Enoch. It involved assessing the reverse passage far-field radiation pattern of a sizeable group of receptors in the back focal plane of the microscope objective. The technique is described briefly in the legend of Fig. 1. When the argument was originally presented, no truly well-oriented human central foveal preparation had been found. Recently, as part of a study conducted in conjunction with Professor H. Ohzu on optical modulation of the human fovea, a nearly perfect specimen was obtained. Its presentation is the subject of this report.

The far-field radiation pattern is the measured distribution of energy (evaluated at infinity) which had been radiated by a given source or collection of sources. Data are usually presented in terms of detector response (logarithmic scale) determined at different angular displacements from the axis of the source. This technique is widely used in microwave optics, and has been applied to the study of waveguide properties in the visual spectrum. The method
Fig. 1. This is a schematic drawing showing the technique used in obtaining Fig. 2. First, one focuses the microscope on the inner boundary of the retinal receptors acting as a fiber optics bundle. The regular eyepiece is then replaced by a telescopic (phase) eyepiece that allows one to look at the back focal plane ($F_L$) of the microscope objective ($L$). In the plane $F_L$, one finds an $x$-$y$ distribution of luminance corresponding to the magnitude of energy emitted at angles $\beta$ (and perpendicular to that, $\lambda$) by the receptors. One then carefully focuses the incident light (a convergent cone of energy subtending angle $\alpha$) upon the ends of the outer segments. The light path is the reverse of that ordinarily traveled by the light (and also the reverse of that ordinarily used to study the retinal modal patterns).

depends on the acceptance of the reciprocity law (reversibility of light path in an optical system). Often, the directionality of a detector may be evaluated more easily by studying its radiation properties as a source. It is this principle which was used in this experiment.

Light was passed in a reverse direction through the receptor array and the receptor far-field radiation pattern was evaluated. The focal plane (back focal plane) of the microscope objective is conjugate with infinity. Just as in the case of the retina, each point in the back focal plane of the objective has a "local sign" or direction associated with it. All energy (from all cells in the array) emitted (secondarily) at a given angle will be focused at a given point in the focal plane. Where overlap is less, the contributions of single cells (modal patterns) may be discerned.

These distributions may be recorded photographically. Microdensitometry allows evaluation of the distribution. The angular equivalence may be determined by imaging known condenser apertures in the back focal plane.

From the Gullstrand schematic eye, we know that a 1 mm. displacement in the entrance pupil of the human eye varies the angle of incidence at the retina by 2.5°. Hence, tentatively the back focal plane distribution may be compared (accepting the reciprocity rule) quantitatively to Stiles-Crawford data (with the limitations considered below).

Previously it was shown that the envelope, or integrated function, obtained in the back focal plane follows the photopic and scotopic Stiles-Crawford functions in
Fig. 3. This is an analysis of the photograph in Fig. 2. The main distribution represents mean microdensitometer determinations (scale to the left). A Stiles-Crawford function (scale to the right) has been superimposed. Angle $\alpha$ is defined in Fig. 1. It has been possible to determine equivalent displacement of a test aperture in the entrance pupil of the human schematic eye and to plot equivalent angle of incidence of the test field at the human fovea.

general shape. As pointed out, the human foveal cone distribution reported previously was not of high caliber.

In Fig. 2, the far-field radiation pattern of specimen A (reference 4) is presented. This photograph was taken (at $\lambda = 500$ nm) approximately 17 minutes after clamping of the optic nerve during enucleation. The central fovea was in excellent condition, and receptor orientation was near perfect. Postmortem effects must have caused some scattering of light. In order to obtain this photograph, the specimen in its chamber was inverted and the condenser was set at $f/4$ (as in the modulation transfer function experiment). (Note: When computing $\alpha$, correction was made for the fact that the retina was immersed in an aqueous medium [tissue culture medium No. 199, Difco Laboratories, Detroit, Mich.].) The central small "hot spot" may or may not be artifactual—preparations have been seen both with and without it. Individual modal patterns are readily discerned on the original where pattern overlap was less marked.

The density profile was measured with an IBM 360-50 computer-controlled optical scanner which centered on the peak of the distribution and at each of 64 intervals (in each meridian) passing through the center of the peak. There was an average of 100 horizontal and 100 vertical scans. In Fig. 3, the left ordinate is logarithmic film density, and the right ordinate gives the values of a superimposed centered and normalized Stiles-Crawford function; that is, $\log \eta = 0.06r^2$ where $r$ is displacement in the entrance pupil (in millimeters).

This optical technique provides a function which is somewhat similar in nature to the Stiles-Crawford distribution. Central zones of pure rod distributions (examined in the back focal plane) are quite flat
when evaluated in a comparable manner. Many questions exist when making this comparison. For example, what role does stray light and light passing between the receptors play in this distribution? Can we assume that optical "summation" (in this optical assembly) and neural summation can be equated? What is the contribution of the single cell to this distribution? In addition to waveguide considerations, a description of the Stiles-Crawford effect must also take into consideration the orientation of the photolabile pigment molecules located in the receptor lamellar discs and the interdigitated pigment lying between the receptors.

Here we assumed that the film density-log exposure (D-log E) curve slope was equal to 1.0. Unfortunately, a D-log E curve was not run on this film batch. (Note: At the bottom of Fig. 3 [where relative film density was limited], exposures were probably falling on the foot of the D-log E curve of the Kodak Plus-X film.)

In summary, this important record encourages further investigation of this technique and of improved means of relating these back focal plane distributions to psychophysical findings. In the near future, the contribution of single cells, or small number of cells, in such displays will be analyzed.

REFERENCES
In press.