Evaluating Diffusion of Light in the Eye by Objective Means

Gerald Westheimer and Junzhong Liang

Purpose. The authors have developed an index of diffusion that describes the relative spread of light inside and outside the region of image focus of the living human eye. It provides in numerical terms a measure of light scatter and can be used to characterize the optical deficit in eyes with age- and disease-related abnormalities of the anterior segment.

Method. An improved version of the double-pass method of examining the aerial image formed by reflection of the retinal image of a point source is employed, together with a new way of analyzing the image. Experimental estimation shows the contaminating effect of backscatter from the media and corneal reflection to be negligible. Measurements are objective and do not require any responses on the part of the patient. Data become available practically on-line.

Results. Index of diffusion values were obtained on 13 patients and varied from 0.22 to 1.04, strongly tending to increase with age. They are rather robust to pupil size, exposure duration, and small amounts of defocus.

Conclusion. The index appears to provide a promising measure of optical performance of the media of the anterior segment of the eye, which might be useful in studying the effect of aging, injury, and disease. Invest Ophthamol Vis Sci. 1994;35:2652-2657.

Most older patients complain of glare and difficulties reading low-contrast print. There are some subjective techniques for diagnosing these defects, but they do not allow one to distinguish explicitly between optical and neural causes. For this reason, we report here on an objective experimental method that is useful for a clinical description of light diffusion in a patient’s eye. The term “diffusion” is employed to cover all light that falls outside the effective region of the diffusion image without distinguishing whether the contribution is due to aberrations or scatter.

The procedure is based on the double-pass method of measuring the light spread in the microscopic image of a slit, first introduced by Flamant. The cumbersome photographic apparatus used by her soon gave way to photoelectric devices, and the procedure has been used widely since (e.g., references 4, 5). Arnulf, Santamaria, and Bescos, while still using photographic methods, extended the procedure to a point rather than to a line source. More recently, video cameras and charge-coupled device (CCD) cameras have been employed. Much progress has been made in estimating the optics of the eye using the double-pass procedure. Though earlier investigators had noticed that scattered light contributed to the double-pass image, this aspect of the problem has not been investigated. In this report, we describe further development of the method and a new analysis of the results to characterize light diffusion in the eye. In addition, we demonstrate ways of using it clinically to characterize age- and disease-related increases in ocular light diffusion with the attendant visual deficits.

The technique uses a low-level laser as the point source and an ultrasensitive, linear CCD camera to capture the image reflected from the fundus, which is then subjected to for practically on-line computer analysis and characterization of the image spread in a patient’s eye. Preliminary results show major differences between normal young patients and older subjects. Finally, we describe a variety of more practical ways of implementing the method for clinical application.

METHOD AND EXPERIMENTAL SETUP. The basic principle of the double-pass procedure is illustrated in Figure 1A. A parallel beam of light is focused by the eye on the retina, and the reflected image is brought, via a beamsplitter, to a focus on the light-detecting device. The retinal image of a point light source, even in optimal focus, is spread out over an area larger than the geometric image, an effect that has roots in a variety of causes, including diffraction, optical aberrations, and scatter in the ocular media. The basic premise of our experiment is that the retina diffusely reflects a small proportion of the light impinging on it. Each point on the retina acts as a reflector, and the light in the detection plane conjugate to the retina will have suffered a double spread, once in each pass through the eye. At the outset one supposes, with a great deal of justification, that the spread is the same in the two directions, in other words, that the aerial image of the retinal image of a point source is the convolution of the eye’s point spread function with itself. The more extensive the diffusion of light in the eye, the wider the double-pass point spread function.
In our implementation, we added a few refinements (Fig. 1B). A high-quality parallel beam was obtained by spatially filtering a laser source, i.e., bringing it to a focus with a good microscope objective on a 0.02 mm pinhole placed in the focal plane of a lens L1. The beam is brought into the eye through a pellicle beamsplitter (PB) and a pair of lenses forming a telescope. The latter permits smooth adjustment of focus to allow for the correction of spherical errors of refraction. The beam returning from the eye passes straight through the beamsplitter and is focused on a scientific grade CCD camera (Princeton Instruments, Princeton, NJ). The pupil diameters for the illuminating and detecting beams can be controlled separately by the two iris diaphragms, I1 and I2.

The CCD camera is composed of an array of 576 X 384 individual photodetectors whose physical dimensions are 20 μ X 20 μ. Each pixel subtends an angle of 11.3 X 11.3 arcsec in the eye’s object space. The CCD detectors are thermoelectrically cooled to −50°C to reduce dark charge to 0.5 signal counts/pixel per second. This allows us to accumulate the signal over time. The CCD output is read digitally by a 14 bit A/D converter directly into the computer without intermediate stages of converting the video signal. The noise associated with the electronic readout of the CCD device is about 1.3 counts/pixel. Low noise and high linearity (better than 1%) in the dynamic range (14 bits) of the CCD device allows us to remove the contribution of the dark charge and the reflection from optical components in the setup by subtracting a background measurement, which then permits a better estimate of the tail of the two-pass aerial image.

We use a 5 mW He-Ne laser emitting light at 638 nm, attenuated by filters, to bring the total light entering the eye to 10 to 20 nW (as measured by a Newport (Irvine, CA) #1815 power meter). Exposure duration was set to be 10 seconds, a value chosen because it gives an acceptable image with good enough signal-to-noise ratio in the central zone in even the worst situation we encountered. The highest total dose is about 3.5 log units below the maximum permissible exposure, according to American National Standards Institute Z-136.1.

The 576 X 384 rectangular array of signal counts, after being read into the computer (Gateway [North Sioux City, SD] 2000 33 MHz 486), is then analyzed by a program, the execution of which takes only a few seconds. First, the pixel with the maximum count is identified. Next, we calculate the average radial intensity distribution centered on this pixel for 36 equally spaced meridia. After normalization to this peak intensity, we obtain a normalized radial intensity distribution. Finally, a cumulative light distribution (encircled energy), summed over all radii and normalized to the total intensity, is calculated as a function of radial distance; the steeper this curve, the more concentrated (i.e., sharper) the image.

At an energy level of 20 nW and for an exposure duration of 10 seconds, the total count in the whole area is of the order of 3 X 10^6 to 5 X 10^6. It depends on the energy in the incident light, the pupil diameter, the reflectivity of the fundus, the transmissivity of the media, and the proportion of the total reflected flux falling outside the area of capture, 109 X 73 arcmin in the eye’s object space. As yet, the partitioning into these factors is not a feasible proposition.

The procedure for acquiring data is uncomplicated and requires the patient merely to remain in the headrest for the duration of the exposure. Spectacle or contact lens corrections could be worn during a session. Blinking reduces the total overall flux and does not enter as a variable in the measurement. Although there are differences in the fundus reflectivity within the general area used for measurement, again they will change the overall reflected flux and not its spatial distribution. However, to stabilize accommodation and enhance the patient’s comfort, and as an aid to standardization, we have provided a small, dim fixation point about 5° above and to the right of the fovea.
so the data from all patients might originate from the same retinal region. We have compared measurements from the fovea and from parafoveal regions and found no difference. The fixation target has about 1/100th the intensity of the main source and does not show up in the reflected image. Because the incoming and returning beams are fixed in the instrument, the patient's head displacement, with consequent changes in pupil alignment, should be avoided. Before each measurement, it is necessary to obtain a readout of the photocell counts with a blank background exposure; the data used for analysis is the difference between the readout under the recording and background conditions.

Participation in this research occurred with the patients' informed consent, in accord with the protocol approved by the University's Committee for the Protection of Human Patients, and in conformity with the tenets of the Declaration of Helsinki.

RESULTS. Figure 2 illustrates the results of the analysis performed on the double-pass image in the right eyes of the two authors. An obvious difference between the two patients is the higher tail in the radial intensity distribution (i.e., the relatively higher proportion of the total returning light that falls into an outer zone) in the older patient. To quantify this phenomenon, we have calculated an

\[
\text{Index of light diffusion} = \frac{E_2}{E_1},
\]

where \(E_2\) is the light captured by the photocells in the annular zone between 14 and 28 minutes of arc radius measured from the peak of the distribution, and \(E_1\) that in the circular zone with radius 14 minutes of arc, again centered on the peak. In the ideal case, when there is no light falling outside 14 arcmins, the index is zero. But when there is diffusion in the eye, more light will fall into the outer zone and less in the central region.

\[\text{Angular Distance in Double-Pass Measurements (min of arc)}\]

**FIGURE 2.** Analysis of the double-pass image of the right eye of the two authors. (A and B): Radial intensity distribution as a function of distance from image peak, averaged for all meridians and normalized. (C and D): Cumulative intensity distributions. (A and C): Subject JL. (B and D): Subject GW.
region. Because the index is the ratio between the two, the more the diffusion (i.e., the poorer the performance of the eye), the higher the index.

Table 1 gives additional details about the measurements in the right eye of the two authors. The cumulative intensity and the index are relatively independent of exposure duration in the range of 0.1 to 10 sec, light energy in the range of 7 to 40 nW, and pupil diameter in the range of 2.5 to 5 mm, but there is a more than four-fold difference in the index between the two observers, even though the visual acuity of the two eyes is similar, about 20/20. It can also be seen that the relative variation of the cumulative intensity for the encircled energy at 14 minutes of arc is small (about 2.5%); a particularly stable index value results from the choice of this diameter.

We have applied the technique to several colleagues, all without clinical defects of the ocular media. Table 2 gives values of the index in these eyes and the patients' ages.

The extensive study of the age distribution of the index remains a program for the future, as does the systematic application to various pathologic entities of the anterior segment of the eye. An indication of the kind of findings that might be expected is the difference between the first and second readings of patient 7. He wore his contact lenses on the first day without any apparent discomfort or visual disability, and not on the second day.

The results so far do not speak to the important question of the nature and actual site of origin of the scatter. But this index is easily measured and is as representative as possible considering the interacting factors of focus, pupil size, fixation, and so on that are involved in a clinical setting.

**DISCUSSION.** In this study, we have attempted to gather into a single number a significant property of light diffusion in the eye. The large increase in light in the tail of the retinal light distribution that occurs in older patients and those with defects in the optical media need not, however, affect the visual acuity, which is mainly determined by the sharpness of the central peak. But it would certainly influence performance in visual tasks dependent on contrast detection in the presence of adjacent bright sources. In setting the central zone, used for the denominator in the index, to a diameter of 14 minutes of arc in the double-pass image, we were guided by both practical and theoretical considerations. Though in fact the actual value of 14 arcmin was not critical, we found in practice that the encircled energy here remained constant for a patient under many variations of measurement. In theory, the single-pass cumulative intensity reaches 98% at 4 arcmin for a pupil diameter of 2 mm when the eye is considered as a diffraction-limited optical system. We expect, therefore, that a disk 14 minutes of arc in diameter in the double-pass image will accommodate almost all the light that falls within the diffraction image for all reasonable pupil sizes, as well as for small amounts of aberration and defocus. This effectively decouples the index from resolution considerations and highlights its intended purpose: characterizing the

### TABLE 1. Analysis of Double-Pass Aerial Image in the Right Eye of the Two Authors

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age (yr)</th>
<th>Cumulative Intensity, Relative to Total, in Aerial Image Within Circles of Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>7'</td>
</tr>
<tr>
<td>1*</td>
<td>68</td>
<td>0.23 ± 0.02</td>
</tr>
<tr>
<td>2†</td>
<td>29</td>
<td>0.62 ± 0.02</td>
</tr>
</tbody>
</table>

* Twelve samples over a 5-month period, intensity between 7 and 40 nW, exposure time 10 sec.
† Twenty-one samples over a 5-month period, intensity between 7 and 40 nW, exposure times between 0.1 and 10 sec, pupil size between 2.5 and 5 mm.

### TABLE 2. Diffusion Index in the Right Eye of 11 Other Subjects

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age (yr)</th>
<th>Cumulative Intensity in Image Within Central 14 Min</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>21</td>
<td>0.78</td>
<td>0.26</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>0.80</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>31</td>
<td>0.78</td>
<td>0.28</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>0.82</td>
<td>0.22</td>
</tr>
<tr>
<td>7*</td>
<td>40</td>
<td>0.62</td>
<td>0.60</td>
</tr>
<tr>
<td>7†</td>
<td>45</td>
<td>0.78</td>
<td>0.28</td>
</tr>
<tr>
<td>8</td>
<td>51</td>
<td>0.64</td>
<td>0.56</td>
</tr>
<tr>
<td>9</td>
<td>51</td>
<td>0.79</td>
<td>0.26</td>
</tr>
<tr>
<td>10</td>
<td>63</td>
<td>0.67</td>
<td>0.49</td>
</tr>
<tr>
<td>11</td>
<td>71</td>
<td>0.62</td>
<td>0.62</td>
</tr>
<tr>
<td>12</td>
<td>75</td>
<td>0.56</td>
<td>0.64</td>
</tr>
</tbody>
</table>

* First day, with contact lens.
† Second day, without contact lens.
scattering of light into regions beyond those used for resolution.

Naturally, the quality of the retinal image suffers when the eye is not in focus. It is necessary to ensure optimal correction of refractive errors during the measurement. Our index of diffusion compares the light in the outer and inner zones of the double-pass image. Based on a series of measurements on two observers, we estimate that up to half a diopter of defocus can be absorbed. The pupil diameter of both the incoming and exiting beams is under the control of the experimenter. The adjustment of these parameters is a problem that this method shares with many objective procedures involving the optics of a patient’s eye. Care should be exercised that the beams stay within the patient’s natural pupil while the measurement is in progress. We have not found very profound effects of pupil size on the index of diffusion and, in any case, it is probably advantageous to obtain measurements in a patient’s natural state of observation.

We have conducted a few tests to estimate the effect of some of the more obvious sources of error. Light is reflected not only from the retina but also from the ocular surfaces, particularly the anterior surface of the cornea, which acts as the most prominent source of light emerging back into the eye’s object space. In our method, the camera surface is conjugate to the retina, and lens L2 collects only a small fraction of the total cone of light specularly reflected from the cornea. This fraction is evenly distributed over the whole CCD surface. We estimated that it contributes about 1 signal count/pixel at a light level of 20 nW at an exposure of 10 seconds. We calculated that removing the contribution of corneal reflex has a negligible effect on the index of diffusion.

It must, of course, be remembered that the objective image captured and analyzed by our double-pass method represents the convolution of the retinal image of a point source with itself. The difficult problem of deconvolution will not be dealt with here except to point out that to a first approximation, for the kind of retinal light distributions that are likely to be involved, the distances quoted here in the eye’s object space would be about half as large when referred back to the retina. The source of the scattering has yet to be investigated in detail, but one of its aspects can be approached with our instrumentation. By a modification, we made the eye’s entrance pupil conjugate to the CCD camera and, at the same time, effectively blocked out the corneal reflex. This permitted us to obtain a comparison of the amount of back scatter in the various patients. We found it to be vary between 1% in the youngest patient and 5% in the oldest, calibrated against the known reflection (6%) from matte black surface. This is consistent with Vos and Allen’s estimate of ocular back scatter, who found it to be age dependent and varying in the 1% to 6% range. Assuming that ocular back scatter has the same angular lobe as matte paper, we can calculate the contribution it makes to the light level in our double-pass aerial image. In Table 3, we provide values of our index in the right eye of the two authors: (a) from the raw data; (b) with corrections made for the contribution to the aerial image from the corneal reflex; (c) with corrections for the contribution made to the areal image from back scatter experimentally determined for the individual eye; and (d) with corrections made for both corneal image and back scatter contributions. The fundamental phenomenon expressed by the index is almost the same under all the conditions, and, under practical conditions, the corrections are not important.

The method described here allows elaborate image analysis but the fundamental datum, the index of diffusion, can in principle be obtained by much simpler means. In particular, the final number is based on the total light captured in just two zones, circular for E1 and annular for E2. There appears to be no reason why this cannot be represented by two single photosensitive surfaces of the right size and shape. A small incandescent source would perhaps be more practical than a laser because its wavelength distribution may be a better indicator for what a patient confronts in daily life. It would appear, therefore, that putting this method into practice in the clinical setting can be simple and inexpensive.

**SUMMARY.** The index is a measure of how efficiently the eye concentrates light from a source without producing unwanted diffusion. Wide diffusion of light in the eye (high index) prevents detection of dim

---

**TABLE 3. Index of Diffusion With Correction of Corneal Reflection and Ocular Backscattering**

<table>
<thead>
<tr>
<th></th>
<th>Index(I)</th>
<th>$I^*_1$</th>
<th>$I^*_2$</th>
<th>$I^*_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW</td>
<td>1.05</td>
<td>1.00</td>
<td>1.00</td>
<td>0.91</td>
</tr>
<tr>
<td>JL</td>
<td>0.21</td>
<td>0.19</td>
<td>0.21</td>
<td>0.19</td>
</tr>
<tr>
<td>R = $I^<em>_1/I^</em>_2$</td>
<td>5.0</td>
<td>5.26</td>
<td>4.76</td>
<td>4.79</td>
</tr>
</tbody>
</table>

* $I^*_1 = \text{Index with the correction of the corneal reflection (1.5 signal count/pixel for both subjects).}$
* $I^*_2 = \text{Index with the correction of the ocular backscattering (1.2 signal counts/pixel for the subject GW, 0.2 signal count/pixel for the subject JL).}$
* $I^*_3 = \text{Index with the correction for both the corneal reflection and the ocular backscattering.}$
* $R$, ratio of the index GW/JL.
and low-contrast targets in the presence of bright ones. The index is, therefore, a promising tool for gauging a patient's capacity for certain demanding visual tasks and also for tracking eye conditions whose effects manifest themselves in increased ocular light diffusion.

Key Words
ocular optics, ocular scatter, index of diffusion, glare

Acknowledgments
The authors thank David Williams, who, with his set-up at the University of Rochester, helped the first author demonstrate the large difference between his and younger eyes and hence the feasibility of this approach. The authors also thank Robert Smith for advice on practical application.

References