Patients With Ocular Hypertension Have Abnormal Point Scotopic Thresholds in the Superior Hemifield

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Purpose. To compare light- and fully dark-adapted thresholds at loci within the central visual field in patients with ocular hypertension and glaucoma.

Methods. Eighteen patients with chronic open angle glaucoma, 13 patients with ocular hypertension, and 24 age-matched normals were studied. The Humphrey automated perimeter with the standard background illumination of 31.5 apostilbs was used to determine photopic thresholds at 18 loci within 20° of fixation. Fully dark-adapted thresholds were measured at the same loci after 30 minutes of dark adaptation by automatic, static campimetry.

Results. The glaucoma group showed elevated scotopic thresholds. Scotopic defects also were found in a significantly higher proportion of patients with ocular hypertension than in normals. These scotopic defects were predominately in the superior hemifield.

Conclusions. Scotopic threshold campimetry may identify the subgroup of patients with ocular hypertension who progress to develop glaucomatous field loss identifiable by standard photopic and mesopic perimetry. Invest Ophthalmol Vis Sci. 1996;37:1608-1617.
strated in eyes with glaucoma.16–17 Prevalent methods of white-on-white perimetry use background illumination in the mesopic or photopic range. There have been conflicting reports on the optimum light level for the detection of early glaucomatous defects. All work to date has only compared photopic to mesopic levels of illumination.18–21 Drum and Armand18 showed that glaucomatous defects at 0.003 candela/m² of background luminance exceeded those at 40 candela/m²; 0.003 candela/m² is in the mesopic rather than the scotopic range. This, coupled with the fact that their patients required only 3 to 8 minutes of dark adaptation to reach steady state, implies that they may have been testing both rod and cone function in their “scotopic test.” There has not yet, to our knowledge, been a comparison between photopic computerized threshold perimetry and fully dark-adapted thresholds at the same loci in glaucoma and ocular hypertension.

In this article, we compare Humphrey perimetry at its standard photopic level of background illumination to computerized scotopic campimetry after 30 minutes of dark adaptation to isolate rod responses completely.

**METHODS**

Patients were recruited from a hospital glaucoma clinic and a private optometric practice. The study was approved by the local ethical committee, informed consent was obtained from all patients, and the tenets of the Declaration of Helsinki were followed. Only one eye of each patient was studied. If both eyes were suitable for inclusion, one was chosen using computer-generated random numbers. Three groups were studied: normals, patients with ocular hypertension, and patients with glaucoma. All subjects in the study were required to fulfill the following criteria: age between 49 and 70 years; best-corrected visual acuity of 6/9 or better; and refractive error < ±7.50 D (equivalent sphere) with less than ±1.50 D cylinder. In addition, normal patients fulfilled the following criteria: normal appearance of the optic disc; normal 30:2 Humphrey field with mean deviation and corrected pattern standard deviation within normal limits on Statpac analysis (P > 10%); intraocular pressure less than 22 mm Hg (minimum of two measurements); no other ocular disease. Patients with ocular hypertension fulfilled the following criteria: normal appearance of the optic disc; normal 30:2 Humphrey field with mean deviation and corrected pattern standard deviation within normal limits on Statpac analysis (P > 10%); intraocular pressure of 22 mm Hg or greater on at least two occasions; no ocular medication; no other ocular disease.

Patients with glaucoma fulfilled the following criteria: typical glaucomatous changes at the optic disc; reproducible glaucomatous field loss demonstrated by Humphrey threshold perimetry on at least two occasions and mean deviation and corrected pattern standard deviation significantly abnormal on Statpac analysis (P < 10%); open anterior chamber angle on gonioscopy; no previous ocular surgery; ocular medication limited to topical beta-blockers only.

All patients had the degree of lens opacity assessed in the eye to be tested using a lens opacity meter (Opacity lensmeter 701; Interzeag AG, Schlieren, Switzerland). This instrument also allowed accurate measurement of the pupil diameter with an eyepiece graticule. The pupil diameter was measured undilated (for the Humphrey field) and 45 minutes after the instillation of 2 drops of tropicamide 1% (for the scotopic thresholds).

Each patient had a 30:2 Humphrey threshold field at the standard background illumination of 31.5 apostils. A large aperture trial frame lens, chosen according to the standard Humphrey criteria, was placed in front of the eye to be tested. The fellow eye was occluded by a black patch. Eighteen loci were extracted from the 30:2 field and from a 10-point custom test to achieve as close a match as possible compared to the 18 positions subsequently used in the scotopic test.

Dark-adapted perimetry was performed in a quiet room that, as much as possible, excluded all external light. There were no windows, and the gaps around the doors were covered with thick black curtains or black tape. The pupil was dilated with 2 drops of tropicamide 1% just before dark adaptation. A large aperture trial frame lens, the spherical equivalent of distance correction plus 3.00 D, was used, and the opposite eye again was occluded. Threshold measurements were made on a modified version of our in-house adaptometer. This adaptometer uses light-emitting diodes (LEDs), operating in a pulsed mode, to produce sequences of precisely defined stimuli under computer control. Such LED adaptometers have been shown to give results that correlate well with conventional adaptometers.24–26

For this study, a Friedmann Mark 1 campimeter was modified to carry the target stimuli. A flat matte black disc with 18 test locations and a central, small, red fixation light replaced the original stimulus plate. The axial eye to plate distance remained at 33 cm. Test stimuli were generated by green LEDs, Stanley EBG 55345 (Stanley Electric Company, Tokyo, Japan), of 5 mm diameter and 555 nm peak emission wavelength. These LEDs were positioned at 10°, 15°, and 20° from fixation along the 45°, 90°, 135°, 225°, 270°, and 315° meridians (Fig. 1) and were covered by 18 dB neutral density filters.

The LEDs were controlled by the microcomputer.
interface of our in-house adaptometer as follows. The LEDs were pulsed on and off within the time period of the stimulus (200 msec). Each 2 μs pulse produced the same light output, and, hence, the total luminance was proportional to the number of pulses within the 200 msec window. Because the pulse repetition rates were in the 285 Hz to 200 kHz range, well above the critical fusion frequency, the stimuli were perceived as continuous. To extend the luminance range further, an additional current step, equivalent to 15 dB in luminance, was added. By varying the number of pulses and using the high- and low-current pulses, the luminance of each LED could be controlled precisely over a range of 42 dB in 2 dB steps.

The initial calibration of the LEDs was performed using a Photo Research PR1500 spotmeter (Kollmorgan, Burbank, CA). First, the magnitude of the current step was measured to 0.04 dB for each LED using a null detection method, and these values were used in calculating the required number of pulses for each stimulus. Second, the internal precision of the generated ramp of stimuli was verified for each LED by counting the pulses per stimulus and by using the photometer to measure various luminance steps to within 0.1 dB. Third, the absolute luminance of each LED was measured on axis. For these small targets, it was difficult to measure the absolute luminances within better than 3 dB using a spot photometer, but this systematic error was the same for all the LEDs and did not affect this analysis. Stimulus intensity was reduced off axis, and, therefore, the viewing angle of each LED had to be taken into account. At 10° of eccentricity, the observed luminance was reduced to 88% of its axial value, at 15° it was reduced to 75%, and at 20° it was reduced to 65%. (Stanley Electric Company data sheet).

A decibel correction factor was calculated for each position and was added to the recorded value to correct for the individual LED luminances and the viewing angles. For this study, the threshold values were expressed as retinal sensitivities, i.e., higher values correspond to lower thresholds, with 30 dB = 0.25 mcd/m², to aid comparison with the photopic data.

After 15 minutes of dark adaptation, a practice run of the test was performed. The patient was asked to maintain fixation on a central red target and the threshold at each of the 18 test positions was determined using a fully automated ascending staircase technique in 4 dB steps. The dark-adapted threshold at each location was taken to be the intensity at which the patient just perceived the stimulus. The threshold for one position was determined before moving to the next. Stimuli were presented in the same random order for each patient. The practice run allowed discussion of any problems the subject might have had before the test. After 30 minutes of dark adaptation, all 18 test points were thresholded again. The initial stimulus intensity was randomly chosen to be 4, 6, or 8 dB below the threshold determined at 15 minutes, and then the fully dark-adapted threshold was found using a 2 dB step algorithm. All 18 points were completed, and the test was repeated twice more. Results from left eyes were reversed laterally to pool them with values from right eyes.

Using data from the age-matched normals, a mean normal light and dark-adapted threshold for each of the locations was calculated, as was an overall mean value for all 18 points. The deviation from normal for individual loci or an overall mean deviation could then be assigned for each patient.

As the photopic and scotopic thresholds at individual test locations were distributed in a Gaussian manner in the normals, a standard deviation could be calculated for each point, and the 95% (−1.65 sd) and 99% (−2.33 sd) lower limits of normal were calculated. These lower limits of normal allowed a scoring system to be used in analysis of the results. Individual location values were scored so that if normal at a level of 

\[ P > 0.05, \text{ the score was 0; if abnormal at a level of} \]

\[ 0.01 < P < 0.05, \text{ the score was 1; and if abnormal at a level of} \]

\[ P < 0.01, \text{ the score was 2. The sum of the} \]

scores for the 18 test positions in each patient was termed the point deviation score (PDS) for the Humphrey or scotopic test.

Eight of the age-matched normal patients were asked to return (an average of 3.5 months after the original test) to assess the repeatability of the results. Full light- and dark-adapted thresholds were repeated.

Statistical analysis was performed using two soft-
TABLE 1. Mean Age, Pupil Diameter, Lens Opacity, Refraction, and Intraocular Pressure in the Three Groups

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Ocular Hypertension</th>
<th>Glaucoma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>24</td>
<td>13</td>
<td>18</td>
</tr>
<tr>
<td>Age (years)</td>
<td>58.4 (7.1)</td>
<td>60.5 (6.1)</td>
<td>61.2 (7.4)</td>
</tr>
<tr>
<td>Undilated pupil diameter (mm)</td>
<td>4.1 (0.9)</td>
<td>3.9 (0.7)</td>
<td>4.2 (0.8)</td>
</tr>
<tr>
<td>Dilated pupil diameter (mm)</td>
<td>6.5 (0.8)</td>
<td>6.4 (0.7)</td>
<td>6.7 (0.8)</td>
</tr>
<tr>
<td>Lens opacity reading</td>
<td>17.8 (5.1)</td>
<td>17.7 (3.8)</td>
<td>18.9 (5.1)</td>
</tr>
<tr>
<td>Refraction (equivalent sphere) (D)</td>
<td>+0.13 (2.1)</td>
<td>+0.65 (2.3)</td>
<td>-0.68 (3.1)</td>
</tr>
<tr>
<td>Intraocular pressure (mm Hg)</td>
<td>15.1 (2.7)</td>
<td>24.8 (1.4)</td>
<td>25.2 (4.5)*</td>
</tr>
</tbody>
</table>

Standard deviations are included in parentheses.

* Before treatment.

ware packages: SPSS-X Version 3 (SPSS, Chicago, IL) and BMDP 1988 version (BMDP Statistical Software, Los Angeles, CA). Univariate analysis of variance (ANOVA) was used to compare intraocular pressure in the three groups. Other variables, such as age, pupil diameter, refraction, and lens opacity reading, were entered into a multivariate ANOVA (Pillai’s trace). Repeated measures ANOVA was used to assess the repeatability of the dark- and light-adapted thresholds at each location. The mean light- and dark-adapted thresholds at each location were compared using one way ANOVA. A Scheffe procedure was used to show which, if any, of the three groups was significantly different from the others. The Scheffe procedure is one of a number of multiple comparison techniques used to analyze further a statistically significant ANOVA result. It is preferred over repeated t-tests, maintaining the overall significance level at a given value (0.05 in this case), while reducing the chances that a true difference between two groups will be missed. The Mann–Whitney test for nonparametric variables was used to assess the PDS between the groups. Individual patients were classified as normal or abnormal on the basis of their PDS results. Chi square analysis with Yates’s correction was used to determine any difference between the normal and ocular hypertensive groups after patients were classified as having either normal or abnormal PDS.

RESULTS

Thirteen patients with ocular hypertension, 18 with glaucoma, and 24 age-matched normal patients were studied. Mean age, dilated and undilated pupil diameters, lens opacity value, refractive error, and intraocular pressure for each are shown in Table 1.

There was a significantly higher intraocular pressure in the groups with ocular hypertension and glaucoma than in the normals (P < 0.05). There was no significant difference in intraocular pressure between the groups with ocular hypertension and glaucoma. There was no statistically significant difference in age, pupil diameter, lens opacity measurement, or refraction between the three groups. To determine which variables had a significant influence on the light- and dark-adapted thresholds, two linear regression analyses were performed on results from normal patients. The independent variables were the mean of the 18 light-adapted thresholds (LAT) and the mean of the 18 dark-adapted thresholds (DAT). The dependent values were age, pupil diameter (undilated for LAT and dilated for DAT), opacity meter value, and refraction.
TABLE 2. Mean of 18 Thresholded Loci

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Ocular Hypertension</th>
<th>Glaucoma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light adapted</td>
<td>29.5 dB (1.5)</td>
<td>29.3 dB (1.1)</td>
<td>19.4 dB (6.6)</td>
</tr>
<tr>
<td>Dark adapted (after 15 minutes)</td>
<td>27.1 dB (1.5)</td>
<td>26.7 dB (1.8)</td>
<td>21.2 dB (4.5)</td>
</tr>
<tr>
<td>Dark adapted (after 30 minutes)</td>
<td>29.5 dB (1.4)</td>
<td>28.5 dB (1.7)</td>
<td>23.5 dB (4.6)</td>
</tr>
</tbody>
</table>

Standard deviations are included in parentheses.

Light-Adapted Thresholds

The mean LATs (along with their standard deviations) at each locus in the 24 normal patients are shown in Figure 2. There was an overall decrease in retinal sensitivity with increasing distance from fixation.

Means of the 18 LATs in the normals and in the groups with ocular hypertension and glaucoma are shown in Table 2. A one-way ANOVA on the mean LAT between the three groups showed that the results were significantly different from each other (P < 0.01). The Scheffe procedure revealed that the glaucoma group was significantly different from both the normal group and the group with ocular hypertension (P < 0.05). The normal group and the group with ocular hypertension were not significantly different from each other.

The mean light-adapted threshold point deviation score (LAT PDS) was 1.1 in the normal group, 1.6 in the ocular hypertensive group, and 22.8 in the glaucoma group. The LAT PDS was significantly higher in the glaucoma group than in both the normal and the ocular hypertensive groups (P < 0.01). There was no significant difference between the LAT PDS in the ocular hypertensive and normal groups (P > 0.05). A LAT PDS of <5 was considered to be within normal limits because this would give a specificity of 96% based on the results of the age-matched normal patients (Table 3). The LAT PDS of 23 of 24 normals and all 13 patients with ocular hypertension was <5 (Table 4). There was no significant difference between the group with ocular hypertension and the normal group in the number of patients with an abnormal LAT PDS (P > 0.05). Only one patient with glaucoma had a LAT PDS <5, resulting in a sensitivity of 94% for the scoring system (Table 4).

In the normal group, the mean of the 9 points in the superior hemifield was 28.76 dB (SD = 1.8) and 30.33 dB (SD = 1.5) in the inferior hemifield. The mean deviation from normal in the age-matched normals was by definition zero for both upper (SD = 1.8) and lower hemifields (SD = 1.5). When a 95% lower limit of normal was calculated for the mean deviation in each hemifield, 23 of 24 normals and all 13 patients with ocular hypertension fell within this normal range for both superior and inferior hemifields Tables 5, 6).

Dark-Adapted Thresholds

The mean DAT and standard deviation for each of the loci in the 24 normal patients after 30 minutes of dark adaptation are shown in Figure 3. There was an increase in scotopic thresholds with increasing distance from fixation.

The mean DAT value of all 18 test locations in the normals was 27.1 dB (SD = 1.5) at 15 minutes and 29.5 dB (SD = 1.4) after 30 minutes (Table 2). This is a statistically significant increase (P < 0.00005). Similar highly significant increases (P < 0.00005) were found for the groups with ocular hypertension and

TABLE 3. Photopic and Scotopic Point Deviation Score in Age-Matched Normals

<table>
<thead>
<tr>
<th>LAT PDS</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Cumulative (%)</td>
<td>58</td>
<td>71</td>
<td>88</td>
<td>96</td>
<td>96</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DAT PDS</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Cumulative (%)</td>
<td>62.5</td>
<td>79</td>
<td>87.5</td>
<td>96</td>
<td>96</td>
<td>100</td>
</tr>
</tbody>
</table>

LAT = light-adapted thresholds; DAT = dark-adapted thresholds; PDS = point deviation score.
TABLE 4. Photopic and Scotopic Point Deviation Scores in the Three Groups

<table>
<thead>
<tr>
<th>Light-Adapted State</th>
<th>PDS &lt; 5</th>
<th>PDS ≥ 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>Ocular hypertension</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>Glaucoma</td>
<td>1</td>
<td>17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dark-Adapted State</th>
<th>PDS &lt; 4</th>
<th>PDS ≥ 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>Ocular hypertension</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Glaucoma</td>
<td>2</td>
<td>16</td>
</tr>
</tbody>
</table>

PDS = point deviation score.

TABLE 5. Analysis of 95% Lower Limit of Normal for the Mean Deviation in the Superior Hemifield

<table>
<thead>
<tr>
<th>Light-Adapted State</th>
<th>P ≥ 0.05 (normal)</th>
<th>P &lt; 0.05 (abnormal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>Ocular hypertension</td>
<td>13</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dark-Adapted State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
</tr>
<tr>
<td>Ocular hypertension</td>
</tr>
</tbody>
</table>

The average DAT PDS was 0.79 in the normals, 2.92 in the group with ocular hypertension, and 13.72 in the group with glaucoma. The DAT PDS was significantly higher in the group with ocular hypertension (P < 0.05) and the group with glaucoma (P < 0.01) than in the normal group.

A DAT PDS of <4 was considered within normal limits because this gave a 96% specificity based on the results of the age-matched normals (Table 3). Twenty-three of 24 age-matched normals had a PDS <4 compared to only 8 of 13 patients with ocular hypertension (Table 4). This excess number of patients with abnormal PDS scores is unlikely to have arisen by chance.
ground illumination in the photopic range at 31.5 apostilbs. The use of computer-modulated LEDs offers several advantages over filament bulbs when used as a stimulus; they have good long-term stability and a fast switching speed. Their relatively low output makes them particularly suitable for testing in the scotopic environment in which the stimulus intensities required are lower than those needed at photopic levels of background illumination. The mean pupil area increased from 17.75 mm² to 21.61 mm² for 60- to 69-year olds. Smaller differences were found in the younger age groups, and larger differences were found in the older age groups.

DISCUSSION

The Humphrey Visual Field Analyser uses a background illumination in the photopic range at 31.5 apostilbs. The use of computer-modulated LEDs proved to be an effective and repeatable method of measuring dark-adapted thresholds at loci within the central visual field, as has been previously reported for peripheral fields.26

Light-emitting diodes offer several advantages over filament bulbs when used as a stimulus; they have good long-term stability and a fast switching speed. Their relatively low output makes them particularly suitable for testing in the scotopic environment in which the stimulus intensities required are lower than those needed at photopic levels of background illumination. The main disadvantage of any scotopic test is the additional length of time required for the eye to become dark adapted. Comparison of our thresholds confirms that this adaptation essentially was complete after 30 minutes but not after 15 minutes. Detailed analysis of results was performed on the 30-minute thresholds. However, the mean thresholds at 15 minutes, based on a 4 dB rather than a 2 dB step algorithm, show a similar pattern across the groups. Further study might, therefore, show that the adaptation time can be shortened. Once the subject was dark adapted, our test took only 5 minutes to threshold 18 loci.

The amount of light entering the eye is directly proportional to the area of pupillary aperture.25 There is less change in pupil area for a given change in pupil size when the pupil diameter is large. For example, the change in pupil area between a diameter measuring 8 mm and a one measuring 7 mm is a factor of 1.3 (50.2 mm²/38.5 mm²). An identical 1 mm change in diameter, from 2 mm to 1 mm, results in a change in area by a factor of 4 (3.14 mm²/0.79 mm²). By pharmacologic dilation of the pupils for the scotopic test, we decreased the relative variation in pupil area to reduce the intersubject variability. Dilation also fixed the pupil diameter so that it could be measured at the conclusion of the scotopic test and the values could be entered into a linear regression analysis.

We did not dilate the pupils for photopic perimetry because this is not done in routine clinical practice, and we wanted to classify our patients into groups of normals, patients with ocular hypertension, or patients with glaucoma on the basis of standard clinical tests. In general, because photopic perimetry measures incremental thresholds, the effect of variations in pupil size should be less significant than that for absolute thresholds. Lindenmuth et al28 studied a group of 18 normals on the Humphrey Field Analyser (30-2 test) with and without dilation with tropicamide. The mean pupil area increased from 17.75 mm² to 47.07 mm², but there was a change of only 0.83 dB in mean deviation. (We are not aware of any similar studies in glaucoma, except those involving patients on myotic agents.)25 Furthermore, there was no significant difference in pupil size between the normal group, the group with ocular hypertension, and the group with glaucoma in our study.

Analysis of thresholds in the normal group showed that the inferior hemifield was more sensitive than the superior hemifield under both photopic (1.6 dB) and scotopic (1.4 dB) levels of background illumination. Katz and Sommer,30 using a Humphrey 30:2 program, found that inferior thresholds were more sensitive than superior thresholds by 1.9 dB in a group of 81 patients (146 eyes) 20 to 78 years of age. Brenton and Phelps31 produced normative data for the Humphrey 30:2 across a broad range of age groups. For the eight locations between 10° and 20° from fixation (not including those points adjacent to the blind spot or the horizontal midline), the inferior hemifield was found to be more sensitive than the superior hemifield by 1.3 dB (50- to 59-year olds) and 1.7 dB (60- to 69-year olds). Zeuge and Drance16 found greater inferior than superior sensitivity in the scotopic range by 1.5 dB for 60- to 69-year olds. Smaller differences were found in the younger age groups, and larger differ-
ences were found in the older age group, but for all patients older than 40 years of age, the inferior hemifield was the more sensitive. Drum et al.\(^\text{18}\) showed the inferior hemifield to be the more sensitive by 0.3 dB after incomplete dark adaptation. It can be seen that our results compare well with these published results for both the photopic and scotopic adaptation levels.

We now return to our comparison of the normal group, the group with ocular hypertension, and the group with glaucoma. These three groups were well matched for age, and there was no significant difference in lens opacity meter reading, pupil diameter, or refractive error among them.

The scotopic PDS and the scotopic mean deviation of the superior hemifield loci revealed significant differences between the normal group and the group with ocular hypertension.

The use of the PDS system allowed greater emphasis to be placed on individual point defects. Scoring individual points did not, however, allow any clustering of defects in particular parts of the visual field to be taken into account. The PDS that resulted in a 96% specificity in the normal group was taken as the upper limit of normal in both the scotopic and photopic tests. When this cutoff was applied to the scores from the group with ocular hypertension, all the light-adapted scores were within normal limits. In the dark-adapted state, however, a significant proportion of patients had abnormally high scores.

Analysis of thresholds in each hemifield showed that the normal group and the group with ocular hypertension could not be distinguished by photopic or scotopic thresholds in the inferior hemifield alone. A significantly higher proportion of patients with ocular hypertension, however, had abnormal superior hemifield scotopic thresholds. Glaucomatous field defects most commonly arise in the superior hemifield,\(^\text{32}\) and it may be that these scotopic defects, identified in a proportion of the group with ocular hypertension, will progress to typical photopic or mesopic defects that can be identified by conventional perimetry. Four of the 13 (31%) patients with ocular hypertension in our study had abnormal mean dark-adapted thresholds in the superior hemifield. This proportion is comparable to the reported incidence of progression to glaucoma in some other series of patients with ocular hypertension.\(^\text{33,34}\)

Glovisky et al.\(^\text{17}\) found abnormally low whole-field scotopic sensitivity to a flickering diffuse white stimulus in 86% of glaucomatous eyes. Patients with ocular hypertension who had abnormal results were more likely to have nerve fiber layer defects or glaucomatous fellow eyes. Their results suggested that absolute scotopic retinal sensitivity is reduced at an early stage of glaucomatous damage and proposed the whole-field scotopic retinal sensitivity test as an effective screening tool. Our study has localized abnormal scotopic thresholds predominantly to the superior hemifield in the group with ocular hypertension.

We have confirmed that glaucomatous eyes have increased point scotopic thresholds. Scoring the dark-adapted thresholds achieved a 89% sensitivity in the detection of the patients with glaucoma. The specificity of our test was 96%. The mean threshold change of 6 dB (Table 2) is less than the 10.1 dB change for the photopic test, but we do not think this weakens our argument that the scotopic threshold changes in patients with ocular hypertension may indicate early glaucomatous damage. The effects of damage or their time courses may well be very different in the photopic and scotopic systems.

The exact pathogenesis of glaucomatous optic nerve damage has yet to be fully elucidated. Histologic studies have shown preferential atrophy of nerve fibers from the upper and lower poles of the optic disc, where the connective tissue support of the lamina cribrosa is known to be weak.\(^\text{35,36}\) There is also evidence that larger nerve fibers in the optic nerve are more susceptible to glaucomatous damage.\(^\text{37,38}\) Axon diameter is related directly to cell body size, and it is the larger ganglion cells that are preferentially damaged.\(^\text{39}\)

The physiological characteristics of retinal ganglion cells have been most extensively studied in the cat model.\(^\text{40}\) The largest cells are the Y cells, which project to the magnocellular layers of the lateral geniculate body. Abnormalities of contrast sensitivity at low spatial frequencies have been found in patients with glaucoma, and the Y cells are particularly sensitive to stimuli of this kind.\(^\text{41}\) Rod signals are preferentially channelled through the Y cells; therefore, the scotopic visual system may be preferentially damaged in early glaucoma.\(^\text{41,42}\) This would be supported by our finding of a significantly higher proportion of patients with ocular hypertension with abnormal scotopic thresholds.

By evaluating fully dark-adapted static automated thresholds, we have tried to isolate the sensory subsystem that manifests early glaucomatous damage. Our results have shown that a significant proportion of patients with ocular hypertension (who by definition have normal Humphrey threshold field results) has abnormal point scotopic thresholds. A longitudinal study is now required to determine whether scotopic campimetry can identify correctly those patients who will later have glaucoma.

**Key Words**

glaucoma, ocular hypertension, perimetry, photopic thresholds, scotopic thresholds
References

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