The visual functions most vital for some everyday activities, such as reading and object identification, depend on the integrity of the fovea and the central macular region immediately around it. However, the test pattern most widely used in static automated perimetry does not adequately sample the macular region. In particular, the points of the 24-2 visual field (VF) test pattern are spaced every 6°. Thus, only 4 points fall within the central 8°, the region in which more than 30% of the retinal ganglion cells (RGCs) reside. Furthermore, these 4 points fall outside the region of highest RGC density as seen with frequency domain (fd) optical coherence tomography (OCT), when the displacement of the RGCs in the fovea is taken into consideration.7,3

This relatively poor sampling of the central 8° would be of little concern if glaucoma did not affect the macular region or, for that matter, if initial glaucomatous damage always occurred outside the central macula region. However, it has been clear for at least 40 years that early, and even initial, macular defects occur in some patients4–9 (see review by Hood et al9). In a study explicitly designed to assess initial defects, Heijl and Lundqvist8 followed up 45 eyes that progressed from a normal to an abnormal VF. Although the largest number of initially abnormal VF points occurred at 15° from fixation, there...
were a number of abnormal points at 5° especially nasally and in the upper VF. More recently, Schiefer et al.\(^\text{10}\) reported that more than 50% of eyes with mild to moderate glaucoma had defects within the central ±3°. In addition, we reported 11 eyes with normal 24-2 VFs outside the central ±10°, but with clear arcuate defects appearing initially within the central 10° as seen with a finer 2° test (10-2) grid.\(^\text{11}\) Furthermore, on fOCT scans, the RGC region within the central 4 points of the 24-2 test was thinner than normal, even in glaucoma suspects with VFs judged to be normal.\(^\text{2,3,11}\)

Practically speaking, the fact that early glaucomatous damage can occur close to fixation would not matter if the 24-2 (6° grid) test did as well as the 10-2 (2° grid) test in detecting early macular damage. However, to our knowledge, there is surprisingly little information on this important point. In a largely overlooked study, Langerhorst et al.\(^\text{12}\) prospectively obtained VF data with both a 30-2 (6° grid) and a 10-2 (2° grid) test pattern. For their patients, who were either glaucoma suspects or showed signs of early glaucoma, 9% of the hemifields classified as normal with the 30-2 were classified as abnormal with the 10-2. Furthermore, the 30-2 test underestimated the severity of glaucomatous damage in 13% of the hemifields.\(^\text{12}\)

Because of the clinical importance of central vision, more information is needed regarding possible macular damage missed with a 6° (30-2 and 24-2) test grid. One purpose of the present study was to compare prospectively the results of 10-2 and 24-2 VF tests in a group of patients with abnormal-appearing optic discs and with 24-2 tests ranging from normal (suspects) to mild glaucomatous defects (mean deviation [MD] -6 dB). In addition, to better understand the nature of early macular damage due to glaucoma, we classified the defects seen on 10-2 VFs and examined the general pattern of damage seen on the VFs.

**Methods**

Because our focus was on early glaucomatous changes, only patients with glaucomatous optic neuropathy on fundus examination and an MD better than -6 dB on 24-2 VF (Humphrey Visual Field Analyzer; Carl Zeiss Meditec Inc) were included in this prospective study. Patients underwent 10-2 VF testing within 6 months of the 24-2 VF or, if 10-2 testing was performed after 6 months, an additional 24-2 VF was performed to serve as a comparison. Both 10-2 and 24-2 VFs use the same test spot size (Goldmann size 3) and background luminance (31.5 asb) and were obtained with the SITA [Swedish interactive thresholding algorithm]-standard test strategy after appropriate refractive correction. Only eyes with reliable 24-2 and 10-2 VFs, defined as fixation losses of 33% or less, false positives of 15% or less, and false negatives of 20% or less, were included. One hundred eyes of 74 patients (average [SD] age, 61.7 [11.8] years) were included in this study. All patients had open-angle glaucoma (abnormal 24-2 VF) or were open-angle glaucoma suspects (normal 24-2 VF). The average MDs on the 24-2 and 10-2 VFs were -2.24 and -2.60 dB, respectively.

Written informed consent was obtained from all participants. Procedures followed the tenets of the Declaration of Helsinki, and the Committee of the Institutional Review Board of Research Associates of Columbia University approved the protocol.

**Classifying 10-2 Visual Fields**

The VFs of the 100 eyes were classified using a cluster rule. Specifically, hemifields were classified as abnormal if there was a cluster of 3 contiguous points (5%, 5%, and 1% or 5%, 2%, and

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**Figure 1. Examples of 10-2 Visual Field (VF) Categories**

A

B

C

All VFs are presented in the right-eye view. The graphs show VFs with loss consistent with an arcutate pattern ranging from arcuate (left) to nasal (right) (A), VF with widespread loss (B), and VFs with temporal loss classified as other (C).
2%) within a hemifield on either total deviation (TD) or pattern deviation plots.

The VF hemifields that failed this cluster test were classified into the following 3 categories based on the pattern/shape of abnormal points: (1) arcuatelike, (2) widespread, and (3) other. The arcuatelike category included arcuate (a continuous, dense defect that involved both quadrants; Figure 1A, left panel); partial arcuate (a continuous defect that involved both quadrants, but was less dense than an arcuate; Figure 1A, middle panel); and nasal (a defect restricted largely to the nasal quadrant; Figure 1A, right panel). The widespread category (Figure 1B) was defined as a loss in all 4 quadrants on both total and pattern deviation plots that did not appear arcuatelike. Abnormal hemifields that did not fall into either of these categories were classified as other. They were predominately scattered across the field or predominately located in the temporal quadrants (Figure 1C).

Additional 10-2 Analyses of the Pattern of Early Glaucomatous Visual Field Damage
At each point of the 10-2 VF, the TD values were averaged across all 100 eyes. In addition, the number of abnormal points with TD values below a criterion level of −3, −5, −15, or −20 dB was calculated.

Results
Prevalence of Central Damage in Early Glaucoma
As seen in Table 1, the agreement among tests was good, with 163 (81.5%) of the hemifields and 88 (88%) of the eyes showing agreement on the 24-2 and 10-2 tests. Figure 2A shows an example of a superior hemifield that was abnormal on both tests. More importantly, abnormal 10-2 VFs (106 hemifields and 76 eyes) were nearly as common as abnormal 24-2 VFs (117 hemifields and 78 eyes). Furthermore, some of the hemifields classified as normal on 24-2 VFs were classified as abnormal on 10-2 VFs. In particular, 13 (15.7%) of the 83 hemifields and 5 (22.7%) of the 22 eyes classified as normal on the 24-2 VF were abnormal on the 10-2 VF (eg, see the superior hemifield in Figure 2B). As expected, 24 (20.5%) of the 117 24-2 VFs classified as abnormal were found to be normal on the 10-2 VF test (eg, see the superior hemifield in Figure 2C). On the 24-2 VF, the prevalence of abnormal superior hemifields (58%) was about the same as abnormal inferior hemifields (59%). However, there were slightly more abnormal superior hemifields (59%) than abnormal inferior hemifields (47%) on 10-2 VFs.

Classification of the 10-2 Visual Fields
The 200 10-2 hemifields were classified as described in the Methods section and the results are shown in Table 2. A similar distribution of defect type was found for superior and inferior hemifields. Of the 106 abnormal 10-2 hemifields, more...
than two-thirds (72 hemifields) were arcuately like. The remaining 34 abnormal hemifields were either widespread (8 hemifields) or other (26 hemifields).

Pattern of Early Glaucomatous Visual Field Damage
To better understand the pattern of early glaucomatous VF damage in the macula and to see whether it conformed to a recent model, the TD values were averaged by location. Figure 3 shows the averaged TD values (left) and the same data in pseudocolor (right). First, all locations show TD values less than zero (mean normal). Second, the deepest defects (yellow and red in the right panel) are in the superior VF and close to fixation. Third, the superior maculopapillary region (blue rectangle) and inferior macular regions are less affected. Finally, the deepest inferior defects are at the nasal edge of the inferior field (within the red borders in the left panel).

The number of eyes with TD values below different criterion levels was also analyzed. Figure 4 shows these results for 4 criterion levels. Notice that the pseudocolor scale is different in each panel in that the darkest red is associated with the most severe TD for each specific criterion level. Consistent with Figure 3, the defects are deeper in the superior field. Furthermore, the pattern of abnormal points is different in the superior vs inferior hemifields (see in particular the data for mild defects [-3 and -5 dB]).

Discussion
The purpose of this prospective study was to examine the prevalence and characteristics of early glaucomatous damage to the macula. In patients classified as suspects or with mild glaucoma based on abnormal discs and VF with MD better than -6 dB, abnormal 10-2 VFs were nearly as common as abnormal 24-2 VFs (Table 1). Similarly, Langerhorst et al found 36% and 48% of the hemifields were abnormal on 10-2 and 30-2 VFs, respectively. Together, these prospective studies support the hypothesis that glaucomatous damage can occur in the macula at a very early stage of the disease. In fact, 81.5% (91.5%) of the hemifields (eyes) we classified as abnormal on either the 10-2 or 24-2 VFs had macular defects as documented by an abnormal 10-2 VF (Table 1).

It is clear that testing with the 24-2 VF alone can miss defects detected on the 10-2 VF. Of the 24-2 hemifields (eyes) classified as normal, 15.7% (22.7%) had defects when tested with the 10-2 VF. Recent fOCT results supply an explanation. In particular, the areas of RGC thinning observed with fOCT in patients with early damage correspond largely to the central 4 test points of the 24-2 VF test.

To better understand the nature of the macular damage, we categorized the 106 abnormal 10-2 hemifields and found that two-thirds of them had arcuately patterns, which included what could be called partial arcuate and paracentral and nasal defects and that the remaining VFs had either widespread loss or other defects (Table 2).

Table 2. Classification of 10-2 Hemifields

<table>
<thead>
<tr>
<th>10-2</th>
<th>Abnormal</th>
<th>Normal</th>
<th>Total No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Arcuate</td>
<td>Widespread</td>
<td>Other</td>
</tr>
<tr>
<td>Superior hemifield</td>
<td>42</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Inferior hemifield</td>
<td>30</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>Total No.</td>
<td>72</td>
<td>8</td>
<td>26</td>
</tr>
</tbody>
</table>

Average total deviation values at each 10-2 location in decibel units (left panel) and as pseudocolor (right panel). The blue rectangle corresponds to the maculopapillary region, which is preserved in the superior hemifield. Both maps are in the right-eye view.
classified as widespread and other. It can even appear as a cecocentral VF defect (see Figure 3 in a study by Hood et al11). Thus, our estimate of two-thirds arcuatelike VF defects underestimates the proportion of RNFL defects that are arcuatelike in terms of RNFL loss. We expect that many of the other and widespread cases would show local RNFL thinning at the disc and an arcuatelike RNFL defect in the macula. On the other hand, we do not mean to deny the presence of diffuse damage, which clearly exists to some mild degree in many patients.14,15 In any case, we cannot reject the hypothesis that early macular damage is due primarily to arcuatelike RNFL damage. This hypothesis needs testing with a prospective study, which would need to include OCT scans.

To understand the pattern of glaucomatous damage to the macula, we have proposed the schematic model3 illustrated in Figure 5A. We called it a schematic because the details of the boundaries are only approximate, are not as sharp as shown, and will vary to some extent across individuals. This model assumes that the RGCs in the inferior retinal region of the macula largely project to the most vulnerable (inferior) region of the disc, while those in the superior region of the macula project to the temporal region of the disc, which is less vulnerable to glaucomatous damage. Outside the central 8° (blue circle), both inferior and superior RGCs project to the vulnerable regions of the disc usually associated with the thick arcuate bundles (red arcs on disc in Figure 5A). In Figure 5B and C, the average TD values (B) and the total number of abnormal points −5 dB or less (C) from Figure 3 and Figure 4 are shown in retinal view and superimposed on the model. The test points are adjusted for the displacement of the RGCs, as previously described.11,16 Although there were only slightly more abnormal 10-2 VFs in the superior (59%) compared with the inferior (47%) hemifields, the pattern and depth of the defects were different and consistent with the model.

**Conclusions**

Macular damage, as seen on 10-2 VFs, appears to occur almost as frequently as peripheral defects in patients with glaucomatous optic neuropathy and/or early glaucoma. Furthermore, approximately 16% of these patients may have undetected central defects when testing functional loss with
24-2 VF alone. This reinforces the conclusion that modification to the 6° grid used in VF tests, such as the 24-2, should be considered.2,3,10 Taken together, the results from the analyses of the frequency and nature of 10-2 VF defects suggest that localized RNFL thinning early in glaucoma can result in both peripheral and central arcuatelike field defects.

A recent model2,3 provided a structural basis for the pattern of macular damage observed. In any case, by using a 24-2 VF alone, clinicians can miss foveal and macular changes occurring before peripheral defects are present. Thus, it is important to use a VF test that better samples the central 10° than does the 24-2 test.

The schematic model describes retinal ganglion cell (RGC) projections from the macula to the disc.2,3 A, The retinal nerve fiber layer (RNFL) bundles (dashed black curves) associated with RGCs outside the macula (blue circle) project to the regions (red arcs) of the superior (S) and inferior (I) quadrants of the disc, which are associated with the most RNFL damage. The RGCs within the gray area with the dark gray border project to the relatively less vulnerable temporal quadrant of the disc, while the RGCs within the white area with red borders project to the more vulnerable inferior quadrant of the disc. B, The schematic model is superimposed on a retinal view of the map of average total deviation values from Figure 3. The 10-2 points have been adjusted for RGC displacement.11,16 C, The schematic model is superimposed on a retinal view of the map of the number of eyes with total deviation values less than or equal to −5 dB from Figure 4. Pseudocolor legends are to the right of each map.

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Figure 5. Schematic Model
REFERENCES


OPHTHALMIC IMAGES

Foveal Injury From a Red Laser Pointer

David R. Lally, MD; Jay S. Duker, MD

The visual acuity of a 9-year-old boy was counting fingers for each eye for 4 days after he stared into a 121-mW red laser pointer. A, Fundus photography reveals a yellow-green foveal lesion with asymmetric radial spokes in each eye. Spectral-domain optical coherence tomography reveals a vertical hyperreflective column in the outer retina of each eye (insets), with an overlying hyporeflective cavity in the left eye. B, At 6-month follow-up, his visual acuity was 20/200 in each eye, fundus photography reveals foveal pigmentary changes, and enhanced-depth imaging optical coherence tomography reveals retinal pigment epithelium migration in the outer retina (insets).