Progression of Local Glaucomatous Damage Near Fixation as Seen with Adaptive Optics Imaging

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Purpose: Deep glaucomatous defects near fixation were followed over time with an adaptive optics-scanning light ophthalmoscope (AO-SLO) to better understand the progression of these defects and to explore the use of AO-SLO in detecting them.

Methods: Six eyes of 5 patients were imaged with an AO-SLO from 2 to 4 times for a range of 14.6 to 33.6 months. All eyes had open-angle glaucoma with deep defects in the superior visual field (VF) near fixation as defined by 10-2 VFs with 5 or more points less than –15 dB; two of the eyes had deep defects in the inferior VF as well. AO-SLO images were obtained around the temporal edge of the disc.

Results: In 4 of the 6 eyes, the edge of the inferior-temporal disc region of the retinal nerve fiber (RNF) defect seen on AO-SLO moved closer to fixation within 10.6 to 14.7 months. In 4 eyes, RNF bundles in the affected region appeared to lose contrast and/or disappear.

Conclusions: Progressive changes in RNF bundles associated with deep defects on 10-2 VFs can be seen within about 1 year with AO-SLO imaging. These changes are well below the spatial resolution of the 10-2 VF. On the other hand, subtle thinning of regions with RNF bundles is not easy to see with current AO-SLO technology, and may be better followed with OCT.

Translational Relevance: AO-SLO imaging may be useful in clinical trials designed to see very small changes in deep defects.

Introduction

For well over 20 years, studies have suggested that the macula (i.e., the central ±8° from fixation) can be damaged in early glaucoma.¹⁻⁵ However, until recently it generally was assumed by clinicians to be relatively uncommon. Witness, for example, the general use in the clinic of a 24-2 (6° grid) visual field (VF), which poorly samples the macula region⁶ and which can miss and/or underestimate the extent of damage.⁵⁻¹⁴ However, recent work with optical coherence tomography (OCT) has documented that macular damage is very common early in the glaucomatous process.⁵⁻¹⁴ In addition, we now have an anatomic explanation for local defects often seen in the superior VF near fixation when patients are tested with a 10-2 (2° grid) VF pattern. In particular, axons of retinal ganglion cells (RGCs) situated in the retinal region just inferior to fixation enter the optic disc in the temporal portion of the inferior quadrant, the quadrant particularly vulnerable to macula damage.⁶⁻¹⁵ Thus, it is not surprising that early glaucomatous defects often are seen near fixation in the superior visual field.

Because the macula is essential for everyday visual tasks, such as reading and driving,¹⁷,¹⁸ it is important to understand the nature of the damage to the macula, especially the deep local defects near fixation. We previously studied eyes with deep defects near fixation as seen on 10-2 VFs with adaptive optics-scanning light ophthalmoscope (AO-SLO) and OCT.
imaging of the circumpapillary region. AO-SLO images have better transverse resolution than do OCT scans, allowing for visualization of the individual retinal nerve fiber (RNF) bundles in healthy and glaucomatous eyes.\textsuperscript{19–25} We found that eyes with relatively similar 10-2 defects and similar circumpapillary RNF layer thickness profiles on OCT disc scans had different degrees and patterns of RNF bundle damage as seen on AO-SLO.\textsuperscript{25} We examined the progression of this damage in the RNF bundles with AO-SLO. In particular, the purpose here was 2-fold. First, using AO-SLO imaging, we examined the change (progress) over time of these deep defects near fixation, and second, we explored in general the use of the AO-SLO in following these changes over time.

### Methods

#### Subjects

Five of the six patients with glaucoma were tested with AO-SLO as part of a previous study,\textsuperscript{25} and they agreed to return for one to three additional AO-SLO imaging sessions. The identifiers (e.g., P1, P2, and so forth) in the present study represent the same patients in the earlier study. For patient P3, both eyes were followed. The times between the first and subsequent AO-SLO sessions are shown in Table 1.

Eyes were selected from a group of 10 eyes with AO-SLO based upon 10-2 VF defects. We were interested in eyes with deep arcuate defects near fixation. All six eyes had deep arcuate defects on the total deviation plot of the 10-2 VF (Humphrey VF Analyzer; Carl Zeiss Meditec, Inc., Dublin, CA), as defined by at least five test points with total deviation values $\leq -15$ dB on their total deviation plots. Figure 1 shows the 10-2 VF total deviation plots for all six eyes; the values less than $-15$ dB are enclosed within the red boundaries. To compare the pattern of defects across eyes, the associated probability plots are presented as right eyes in

### Table 1. Time in Months between First and Subsequent AO-SLO Imaging Sessions

<table>
<thead>
<tr>
<th>Patient</th>
<th>Eye</th>
<th>Second Visit</th>
<th>Third Visit</th>
<th>Fourth Visit</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>OS</td>
<td>14.7</td>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>OD</td>
<td>14.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P3OD</td>
<td>OD</td>
<td>17.3</td>
<td>22.8</td>
<td>33.6</td>
</tr>
<tr>
<td>P3OS</td>
<td>OS</td>
<td>4.9</td>
<td>15.5</td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td>OS</td>
<td>26.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P6</td>
<td>OS</td>
<td>19.1</td>
<td>27.4</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. 10-2 visual field total deviation plots. The points close to fixation with total deviation values $\leq -15$ dB are enclosed within the red borders in the upper (solid) and lower (dashed) hemifields.
Figure 2 (i.e., left eyes were flipped along the vertical meridian). All six deep defects were within $3^\circ$ of fixation. In fact, in four of these eyes, the defect included the test point closest to fixation at the right ($1^\circ, -1^\circ$) and left ($1^\circ, 1^\circ$) eyes. These 10-2 VFs were obtained on the same day as the first AO-SLO session for patients P3OS and P5, and within 3 weeks (patient P1), 9 weeks (patient P2), 4 days (patient P3OD), 7 months (patient P4), and 9 weeks (patient P6) for the other eyes.

Inclusion criteria for AO-SLO imaging were best-corrected visual acuity better than 20/40, clear media, refractive error within $6.0$ D, and pupil dilation $\geq 6$ mm. Patients with intraocular lens implants were excluded. All patients were on intraocular pressure (IOP) lowering medication and there was no reason to suspect they were not compliant. In addition, two eyes had laser treatment during the follow-up period. Patient P1 had selective laser (SLT) and argon laser (ATL) trabeculoplasty between AO-SLO sessions two and three, and patient P3OD had SLT between AO-SLO sessions 1 and 2. Table 2 contains the diagnosis, age at the first AO-SLO session, IOP at each AO-SLO session, range of IOP over all intervening visits, and systemic and ocular comorbidities.

Written, informed consent was obtained from all participants. Procedures followed the tenets of the Declaration of Helsinki, and the protocol was approved by the institutional review boards of

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Table 2. Diagnosis, Age at First AO-SLO Session, IOP and Comorbidity Information

<table>
<thead>
<tr>
<th>Patient</th>
<th>Eye</th>
<th>Dx</th>
<th>Age, First Visit</th>
<th>IOP, d of AO</th>
<th>IOP, range</th>
<th>Systemic and Ocular Comorbidities</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>OS</td>
<td>PG</td>
<td>59.2</td>
<td>13,15,10</td>
<td>10–18</td>
<td>OSA on CPAP; hypothyroid</td>
</tr>
<tr>
<td>P2</td>
<td>OD</td>
<td>OAG</td>
<td>53.4</td>
<td>16,19</td>
<td>15–19</td>
<td>Disc hemorrhage 8 y before to first AO-SLO session</td>
</tr>
<tr>
<td>P3OD</td>
<td>OD</td>
<td>OAG</td>
<td>43.3</td>
<td>14,23,20,18</td>
<td>14–23</td>
<td>Ocular surface disease associated with glaucoma medications</td>
</tr>
<tr>
<td>P3OS</td>
<td>OS</td>
<td>OAG</td>
<td>43.3</td>
<td>17,18,15</td>
<td>12–19</td>
<td>Ocular surface disease associated with glaucoma medications</td>
</tr>
<tr>
<td>P5</td>
<td>OS</td>
<td>NTG</td>
<td>65.9</td>
<td>19,13</td>
<td>11–19</td>
<td>Migraines</td>
</tr>
<tr>
<td>P6</td>
<td>OS</td>
<td>OAG</td>
<td>63.2</td>
<td>14,26,20</td>
<td>12–20</td>
<td>OSA on CPAP</td>
</tr>
</tbody>
</table>

CPAP, continuous positive airway pressure; NTG, normal tension glaucoma; OAG, open angle glaucoma; OSA, obstructive sleep apnea; PG, pigmentary glaucoma.
Columbia University and the New York Eye and Ear Infirmary of Mount Sinai.

AO-SLO Imaging

After pupil dilation, the RNF bundles were scanned using a custom-built, confocal AO-SLO system, as described previously. In particular, RNF bundles were imaged near the edge of the optic disc, along the temporal half of a circle at approximately 1.7 mm from the disc center, and if time permitted along a vertical line through the fovea. (The vertical imaging was a secondary measure as the RNF bundle thinning was less distinct in this region compared to the circum-papillary region where RNF bundles are thicker before damage.) The images were captured using $1.5^\circ \times 1.5^\circ$ and $1.0^\circ \times 1.0^\circ$ fields of view for the disc and macula, respectively. The retinal depth at which each patient was imaged was determined by adjusting focus. In particular, to ensure the innermost retinal nerve fiber layer (RNFL) surface was imaged for each subject, the adaptive optics (AO) focus was started just above the RNFL (i.e., at the vitreous) and then slowly shifted toward the surface of the RNFL.

Each image was the average of a sequence of frames with the highest signal-to-noise ratio. These images were montaged manually and coregistered with fundus photographs. Images from different scan dates also were aligned with the same fundus photograph using blood vessels as landmarks.

Results

Progress of the Edge of Deep Defects Near Fixation as Seen on AO-SLO

Figure 3A shows the montage of the AO-SLO images of patient P3OD obtained during the first (left) and last (right) AO-SLO visits. Figures 3B and 3E show an enlarged image of the region within the red and green squares in Figure 3A, and Figures 3C and 3D show the images for the same region obtained on the second and third visits. On the first visit, there is a region largely devoid of RNF bundles; the yellow lines indicate the approximate superior (solid) and inferior (dashed) borders of this region. To help visualize the changes over time, corresponding regions are indicated in Figures 3C to 3E. The red dots indicate blood vessel locations, the yellow double arrows show the width of the region with largely missing RNF bundles at two locations on the first visit, and the red arrows show the same location in Figures 3B to 3E.

There appears to be progression of the RNF bundle loss during the 17.3 months between the first (Fig. 3B) and second (Fig. 3C) visits and during the 10.8 months between the third (Fig. 3D) and fourth (Fig. 3E) visits. The abnormal region (red arrows)
above the solid yellow line becomes larger over time. Notice that there appears to be little change during the 5.5 months between the second (Fig. 3C) and third (Fig. 3D) visits. Three of the remaining five eyes (patient P3OS, Fig. 4; patient P2, Fig. 5; patient P1, Fig. 6) showed suggestions of progression of the edge between regions of missing bundle and largely present bundles in the same inferior-temporal region of the disc. The red arrows in Figures 4 to 6 show locations with an apparent loss of RNF bundles over time. That is, in each eye there are RNF bundles near the tip of the red arrow at the first visit and these bundles are less apparent over time.

In one of the two remaining eyes (patient P5) the presence of an epiretinal membrane (ERM) made it difficult to follow changes in the inferior temporal region as seen in Figure 7. In the other (patient P6, Fig. 8), the border between a clearly seen bundle (yellow arrows) appears to remain the same after 27.4 months.

**Progressive Loss of Contrast of RNF Bundles within Defects Near Fixation as Seen on AO-SLO**

In patient P6 (Fig. 8), the bundles in the region of the green arrows become less distinct (less contrast)
between the first and last images. In addition to patient P6, patient P3OS (Fig. 4) also showed evidence of a loss of contrast in the remaining RNF bundles. For example, compare the regions near the green arrows at the first and last visits. The bundles lose contrast and become harder to discern over the 15.5-month period. On the other hand, there appears to be little change between the images from the first and second visits, which were only 4.9 months apart.

**Superior Disc/Lower VF Defects**

Two eyes (P1 and P3OS) also had deep arcuate defects near fixation in the inferior 10-2 VF (Figs. 1, 2). In both cases, the edge of the high contrast bundles changed/moved over time as seen by the red arrows in Figure 9. In addition, in both eyes there was an indication of a change in contrast of the bundles in the affected area (green arrows).

Further, note in Figure 7A there also is a region (green arrows) in the superior disc with a clear change in contrast between the two test dates. This disc region is outside the area associated with the 10-2 VF. Progression was seen in the associated region on 24-2 VF and OCT scans (not shown).

**Discussion**

Our primary purpose was to understand the nature of glaucoma progression in terms of RNF loss as seen with AO-SLO. We identified two aspects of progression of deep defects near fixation. First, in four of the six eyes, the edge of the region with healthy-appearing RNF bundles moved in the direction of fixation. That is, we have evidence of subtle progression of damage toward fixation within 10.6 (patient P3OS) to 14.7 (patient P1) months in these four eyes. In addition, within the abnormal regions there also was a suggestion of a loss of contrast of the remaining bundles over a similar time period.
Both types of change seen on AO-SLO are consistent with what we know about glaucoma progression. The loss of RNF bundles at the edge of the defect very likely is associated with the increase in the area of damage seen on OCT scans and VFs. However, we must exercise caution in interpreting the loss of contrast of bundles within the defect, as contrast can be influenced by several factors, including the plane of focus and variations in the brightness and contrast of AO-SLO images. Irrespective of these, it is likely that at least some of this decrease of contrast is due to a loss of RNF axons, as we know that a thinning on the RNFL seen on OCT scans can be associated with a lower contrast seen on AO-SLO images. This is illustrated for patient P3OD in Figure 10, where the image on the right is a portion of the AO-SLO image from Figure 3A (left), and the image on the left is a portion of a circumpapillary OCT circle scan of the same region from a previous study. The violet lines show corresponding locations of two blood vessels, which border the region of lower contrast on the AO-SLO image and thinner RNFL on the OCT scan.
Comparison of AO-SLO Images to VF and OCT

These subtle changes at the edge of the defects seen on AO-SLO will be hard to see on traditional VFs, even with the 10-2 test pattern. To illustrate this point, Figure 11A shows the circumpapillary AO-SLO images from Figure 3A and the AO-SLO images along the vertical meridian taken in the same session. The white dots indicate the estimated locations of 10-2 visual field points in the region of interest, while the red dots are the two locations shared by the 10-2 and 24-2 VFs. The locations of the VF points have been adjusted to take into consideration the displacement of the ganglion cells near the fovea. The white line is the approximation of the course the RNF axons take above the edge of the defect. (B) An enlarged image of the region within the green rectangle. (C) The same region 17.3 months later. The yellow arrows in (B) and (C) are in the same location. Scale bar: lower right of (A) 500 μm.

Figure 11. (A) Montage of the peripapillary AO-SLO images superimposed upon the fundus photograph of P3OD from the first visit (as in Fig. 3A) along with the montage of the AO-SLO images obtained along the vertical meridian. The white dots indicate the estimated locations of 10-2 visual field points in the region of interest, while the red dots are the two locations shared by the 10-2 and 24-2 VFs. The locations of the VF points have been adjusted to take into consideration the displacement of the ganglion cells near the fovea. The white line is the approximation of the course the RNF axons take above the edge of the defect. (B) An enlarged image of the region within the green rectangle. (C) The same region 17.3 months later. The yellow arrows in (B) and (C) are in the same location. Scale bar: lower right of (A) 500 μm.

Figure 12. (A) An en face OCT image obtained for P3OD by averaging the reflectance intensity of a region (slab) between the ILM and 52 μm below the ILM. (B) Montage of the peripapillary AO-SLO images superimposed upon the fundus photograph of patient P3OD for the first visit (as in Fig. 3A). The green rectangles and arrows in both Figures are the same regions of the superior temporal (arrows) and inferior temporal (rectangles) disc. The yellow and red arrows show regions of missing (red) RNF bundles and bundles of low contrast (yellow).

Figure 12. (A) An en face OCT image obtained for P3OD by averaging the reflectance intensity of a region (slab) between the ILM and 52 μm below the ILM. (B) Montage of the peripapillary AO-SLO images superimposed upon the fundus photograph of patient P3OD for the first visit (as in Fig. 3A). The green rectangles and arrows in both Figures are the same regions of the superior temporal (arrows) and inferior temporal (rectangles) disc. The yellow and red arrows show regions of missing (red) RNF bundles and bundles of low contrast (yellow).
yellow arrows show clear RNF bundles at the first visit (Fig. 3B), but little or no indication of bundles 17.3 months later. Notice also that there are a number of such bundles between the points of the 10-2 VF. Thus, the 10-2 will not be able to resolve some of the details seen on AO-SLO.

OCT also has better spatial resolution than the 10-2 VF. However, the lateral/transverse resolution of the OCT is poorer than that of AO-SLO, so that details in that direction will not, in general, be seen as well. In any case, a good way to visualize the local variations in RNF thickness and intensity on OCT scans is with en face images obtained by averaging the OCT reflectance intensity in a slab of constant width below the inner limiting membrane (ILM). Figure 12A shows the en face image obtained for patient P3OD from a swept-source OCT scan obtained on the same day as the AO-SLO images in Figure 3A, which are reproduced in Figure 12B. The en face image in Figure 12A was based upon a nominal 9 × 12 mm scan with 256 b-scans, each with 512 a-scans. When comparing the same location in the inferior temporal region of the disc (green rectangle), the same pattern of RNF loss is apparent on the OCT en face (Fig. 12A) and AO-SLO (Fig. 12B) images. However, the details are seen better on the AO-SLO image. While the resolution of these details can be improved by increasing the density of the a- and b-scans, we expect that it will not equal that obtained with high quality AO-SLO images.

On the other hand, there is a pattern of arcuate losses in the superior retina of this same eye that arguably is easier to see on the OCT en face image. Compare the regions indicated by the green arrow on the en face (Fig. 12A) and AO-SLO (Fig. 12B) images. It is easier to visualize an abnormal region on the complete en face image in Figure 12A. To be fair, this en face image has the advantage of a wide view that helps to identify the abnormal regions. Thus, a proper comparison requires a larger montage of AO-SLO images, which would take considerable time to obtain. In any case, it not surprising that a decrease in thickness may be easier to see on OCT given it has better axial resolution than does AO-SLO.

Clinical Implications

Our secondary purpose was to explore the use of AO-SLO imaging in detecting progression in the clinic or clinical trials. As previously noted, it has a limited role with current technology. First, patients cannot have dry eyes, high refractive errors, significant cataracts, or ERM. Further, the circumpapillary images take over 45 minutes to obtain and many hours to analyze. However, Chen et al. speculated that AO-SLO imaging of a restricted portion of the disc might be of use in small clinical trials designed to monitor progression. Our results suggested that it may be of value when it is important to detect very early changes in deep arcuate defects. In particular, no other current technology allows us to see the loss of individual RNF bundles with the same detail. On the other hand, we would add to the caveats above that subtle thinning might be difficult to detect with AO-SLO and that OCT measures, including combined AO and OCT, might actually be superior for detecting these changes; they will certainly be quicker and easier to obtain and analyze.

Limitations

This study has two main limitations. First, the sample size is small. Second, the analysis is qualitative. While the movement of the edge of the defect should, in principle, be possible to quantify, the detection of contrast is more complicated. In any case, even if contrast changes due to RNFL thinning are reliably distinguished from other sources of contrast variations, it is unlikely that AO-SLO will be superior to OCT for detecting RNFL thinning for reasons mentioned above.

Conclusions

Progression of damage of deep arcuate defects near fixation is manifested on AO-SLO images in two ways. Over a period of approximately 1 year, there is a loss of individual RNF bundles at the edge of these defects. In addition, bundles remaining in the region of the defect lose contrast. These subtle changes will not be detectable on a 10-2 VF, and may or may not be seen with OCT en face imaging. On the other hand, subtle thinning of the RNFL is not easy to see with current AO-SLO technology and probably is better followed with OCT.

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