Landmark-Driven Fundus Perimetry Using the Scanning Laser Ophthalmoscope

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Purpose. To present a new method of performing scanning laser ophthalmoscope perimetry that compensates for eye movements so that the correct retinal location is tested even if fixation changes. This allows for accurate testing of patients with central scotomas and for repeating testing longitudinally at the same retinal locations even if central fixation is lost.

Methods. The operator views the retina and selects a retinal landmark, such as a vessel bifurcation, that can be identified easily. A testing strategy is preselected, and the computer saves the landmark and stimulus coordinates. To present each stimulus, the operator positions a cursor over the retinal landmark, and the computer adjusts the site of presentation of the stimulus for any change in landmark position caused by an eye movement. At the conclusion of the testing, the results are displayed in the proper retinal location on a fundus image.

Results. Sixty-seven eyes with macular disease were tested with the landmark-driven method, using the same preplanned strategy for each eye for both a bright and a dim stimulus. There was a low rate of inconsistent points (seen with dim but not bright stimuli), and virtually all of these bordered a dense scotoma. Those eyes with more inconsistent points had a significantly greater percentage of dense scotoma points and significantly lower visual acuity. The technique significantly corrected error in retinal localization resulting from large eye movement. There is no significant rotation or magnification change during the procedure, so specifying the change in location of one landmark is sufficient to describe movement of the retina. The technique is rapid and easy to administer to elderly patients and to children.

Conclusions. This technique allows for accurate and repeatable measures of retinal sensitivity in specific locations. It is useful in following change over time. It can be developed further to allow for fully automated, retinally correct testing. Invest Ophthalmol Vis Sci. 1995;36:1863–1874.

Visual field measurement provides important information regarding the diagnosis, progression, and management of many ocular diseases. Most notably, visual fields are extremely important in glaucoma to diagnose and evaluate the progression of disease, in neuroophthalmologic disorders to aid in the determination of the site of involvement in the eye, optic nerve, or brain, and in some retinal diseases, such as retinitis pigmentosa, to assess the extent of involvement and visual disability. These evaluations are well served by our current methods of visual field determination, herein referred to as conventional visual field testing, which include Goldmann kinetic perimetry, Humphrey static perimetry, and similar techniques.

However, conventional visual field determination is inadequate for the accurate evaluation of macular disorders or any retinal disorder in which foveal vision is compromised and the patient may have unstable fixation or extrafoveal fixation. Accuracy of the conventional visual field relies on the assumption that fixation is foveal and stable. If fixation is not foveal, the conventional visual field will still be mapped as though fixation is at the center (0°) of the field, so that all points tested will be shifted relative to their true retinal location. (A perimeter that uses the blind spot to test fixation may register fixation losses, but it is unable to correct for these.) If central fixation is
visualization of the fundus and the precise location of vision, may not detect the presence of a scotoma. 1’2 Grid, used as a screening test for changes in central vision, may not detect the presence of a scotoma. 1’2 Pericentral fixation lines to facilitate a patient’s centering on the fovea often still result in eccentric fixation. 3

Fundus perimeters are devices that provide for visualization of the fundus and the precise location of the stimulus on it. One can then see the exact test site on the retina and can correlate visual field defects to their true retinal positions. 3 Several fundus perimeters have been designed and used in the past 30 years. 5–14 The scanning laser ophthalmoscope (SLO) is the most recent and well-known fundus perimeter. It has allowed us to gain new information regarding the nature of visual loss in various macular diseases, including age-related macular degeneration and macular holes. 1’6’7’15–25 However, because of difficulties in dealing with the additional data provided by SLO testing, methods of performing fundus perimetry have not used and have even ignored the advantage of viewing the fundus during testing. These difficulties include how to evaluate data correctly when the stimulus does not fall on the desired retinal location because of eye movement, how to ensure that the desired retinal areas are tested, and how to summarize the data. An additional problem is how to test for scotomas that might not correspond to observable lesions rather than simply testing over or at borders of retinal lesions. A number of investigators have shown that in diabetes 26–29 and other macular diseases, 30 scotomas may be present that do not correspond to observed retinal lesions; this is undoubtedly true in other retinal diseases, and these areas would be missed by testing only over observed retinal lesions. Finally, there must be a reliable method to test over the same retinal points when testing is repeated, even if fixation has shifted, to assess change over time.

Scanning Laser Ophthalmoscopy and Previous Fundus Perimetry

In the SLO, two coincident thin laser beams rapidly scan the retina. A nearly invisible infrared laser is used for imaging the retina, and a visible helium neon (HeNe) red laser is used for presenting the stimulus for psychophysical testing. The intensity of the HeNe beam at each retinal point is controlled by the computer. The stimulus is created by modulating the HeNe laser beam to produce spots, letters, words, or any desired pattern, with maximal resolution of 2 minutes of arc (corresponding to 1 pixel, and to 10 μm on the retina) for our system. The operator views the SLO retinal images on a monitor, with the stimulus as part of the image. A fixation cross is placed in the center of the field by the HeNe laser beam. (The cross can be placed anywhere within the field, but we routinely use it in the center.) The operator can then see which retinal location is used to fixate the cross and when a patient has changed fixation. One also can see where a stimulus falls on the retina, and one does not have to correct indirectly for eye movements. One may observe whether the eye moved significantly during the stimulus presentation, and one can repeat testing in desired locations relative to fixation.

The powerful advantages of testing with the SLO also are a source of challenge to use the SLO’s capabilities, and the data obtained, to the maximum. First, the SLO provides the means of testing identifiable fundus lesions—such as scars, drusen, macular holes, and choroidal neovascularization—reliably. The investigator has a natural bias toward assuming that scotomas will correspond exactly to these lesions and may test in a way to maximize this outcome—for instance, by heavily testing along borders, by ignoring normal-appearing areas, or by repeatedly testing a single location. To cover the central field adequately, it is necessary to plan areas to be tested. A second challenge is how to test the desired retinal positions despite eye movements. 30

Another major challenge has been how to generate a final overall map of the perimetry results. One approach is to transcribe manually the location and result at each point tested onto a hard copy of the fundus image, 1 but this is subject to transcription error and to bias based on the location of retinal features. Another approach is to ignore the eye movements that may occur and to plot the absolute coordinates of the points tested on the monitor 7’10’21 (for example, by overlying an acetate sheet on the monitor and marking points tested), but if this neglects the advantage the SLO provides in correcting for eye movements, it does not differ from conventional perimetry. A third approach is to videotape the testing session and then review the tape and note the retinal location of each stimulus presentation, 9 but this is tedious.

Most SLO studies have used kinetic perimetry techniques. The limitation of kinetic testing is that one does not know the location of the stimulus to which the patient responded because reaction time and other factors are involved. Thus, the kinetic maps of some lesions by SLO are necessarily imprecise. 2’3’4 Static perimetry has the advantage of testing only one retinal site at a time, limited by the degree of eye movement during stimulus presentation, but full static perimetry to determine the threshold at each point takes a long time and would limit the number of locations that can be tested. For this reason, we have...
adopted the technique of mapping out an isopter using static flashes of light. We select a single stimulus intensity for all our test locations for each stage of testing, as in kinetic perimetry, but we present single flashes as the stimulus, as in static perimetry. This allows us to obtain information on precisely located retinal sites, as in static perimetry, but at a larger number of locations at the expense of obtaining full threshold values.

As an initial step to improve the precision of SLO fundus perimetry, we developed the following procedure. At the start of the test, two retinal landmarks, such as vessel bifurcations, are selected (to ensure that at least one landmark is visible even if the eye moves). The examiner moves the cursor to the desired test location and presses a mouse button to present the stimulus. The computer grabs a fundus image at the end of stimulus presentation, and the examiner then moves a cursor to one of the two retinal landmark locations. The computer stores the actual coordinates of each stimulus and the coordinates of the landmark at that time. When testing is completed, a final fundus image is grabbed. The retinal landmarks are identified, and the computer displays each of the stimulus points on this fundus image, shifted to the correct retinal location based on the landmark location at the time that point was tested. Thus, when the summary data are displayed, the examiner can see whether the correct points were tested and can test further until all the desired retinal features are tested. The disadvantage of this method is that it significantly prolongs the testing session because the examiner first has to position the cursor on the retinal location of interest and then position a cursor on the retinal landmark for each stimulus presentation. The desired points are not necessarily tested when eye movements intervene. In addition, neither this method nor the others mentioned lend themselves to a systematic evaluation of the central field. Finally, a recent study of fixation stability in patients with low vision (see Discussion section) suggests that significant eye movements are more likely to occur toward the end of stimulus presentation, causing an inaccurate mapping of stimulus location on the retina.

We have developed a new technique for testing with the SLO, landmark-driven fundus perimetry, that allows for planning a grid of points or a customized testing plan before beginning the test, for the random presentation of stimuli, for the use of retinal landmarks to guide the placement of stimuli, and for reliable mapping and recording of the retinal location of scotomas. In addition to the advantages this procedure has for any given testing session, it has the capability of testing the same retinal locations longitudinally over time. We think that these techniques allow for more accurate and rapid SLO testing and that they will ultimately allow fully automated, retinally correct scotoma mapping using computerized pattern recognition of retinal landmarks.

METHODS

Calibrating the Scanning Laser Ophthalmoscope

A description of the SLO has been provided in the introduction. Some calibrations are necessary to be certain the stimulus conditions are as desired. To calibrate the stimulus intensity, a power meter is used to measure the laser power at the position corresponding to the front surface of the eye in steps spanning the 256 gray scale levels. The calibration of the retinal illuminance function is similar to the calibration of the luminance function of a monitor driven by a digital-to-analog converter. The general shape of the power versus gray scale level function seems to be invariant over time, whereas the DC level of the laser power can change. To test at a specific retinal illuminance, one determines the gray level that would correspond to that illuminance (by inverting the function). With our laser acousto-optic-modulator system, we have a dynamic range of slightly less than 5 log units, with maximum power of approximately 50 μW/sq cm, corresponding to approximately 70,000 td.

The minutes of arc per pixel is calibrated by projecting the raster field on a screen and computing the horizontal and vertical field angles. This must be divided by the actual addressable pixels in the SLO field, which is often less than 512 × 480 because of blanking of some top and bottom raster lines and occasionally of some side pixels.

Landmark-Driven Fundus Perimetry

An encapsulation of the difference between uncorrected perimetry and landmark-driven fundus perimetry is given in Figure 1, which shows (left) the retinal region that the operator desires to test. In addition, two landmarks (retinal vessel bifurcations) have been identified by the operator. When the stimulus is to be presented, the eye position has changed. This leads to the two landmarks occupying new positions relative to the monitor (Fig. 1, center). The operator positions the cursor on one new landmark location, and the computer adjusts the stimulus position so that it moves to compensate for the eye movement (Fig. 1, right). The stimulus is presented at the correct retinal location (black square) instead of at an incorrect retinal position (shaded square) as is the case in conventional uncorrected perimetry. The components of our technique are as follows:

Preplanned Testing Strategy and Randomization of Points To Be Tested. A preplanned testing strategy pro-
FIGURE 1. Landmark-driven fundus perimetry. (left) The patient fixates the fixation cross, with a surrounding c-shaped area of scotoma (dotted curve). The large rectangle is the area seen on the monitor (corresponding to the small field size on commercial SLOs). The small solid square indicates the point to be tested. Two retinal landmarks (A and B) are selected by the operator. (center) At the time of testing, the retina has shifted downward. The retinal landmarks have changed, relative to their original positions on the monitor, from A and B to A' and B', respectively. B' is now outside the field seen in the monitor. (right) The operator places the cursor on the new landmark location (A'). The computer corrects the location of the stimulus presented to its correct retinal location (black square). If uncorrected for eye movement, as in conventional perimetry, the stimulus would fall on the incorrect retinal position (shaded square).

vides the ability to select those areas most important for testing and to test in a uniform way. It provides comparable information on different patients with the same disease, which is important for enhancing clinical knowledge of a disease process and for research on the progression or characteristics of a disease. It allows for monitoring changes over time at specific points. For example, in age-related geographic atrophy, a form of advanced age-related macular degeneration, scotomas often develop that surround the fovea but spare the foveal center until late in the course of the disease. For this disease, a circular grid of points centered on fixation provides a good map of the loss of function and of change over time. For other diseases, a rectangular grid of points may be more appropriate. Randomization of points maintains spatial uncertainty, as it does in conventional visual field techniques. It also allows confidence that a region with several scotomatous points is a true scotoma and is not the result of the patient being distracted for one period of time.

The steps for the preplanned strategy are as follows:

1. **Grabbing a fundus image.** The patient's eye is aligned in the apparatus, and the patient is instructed to look at the fixation cross (1° in extent). A fundus image is grabbed and is used to set up the testing strategy (while the patient relaxes).

2. **Choosing retinal landmarks.** The investigator chooses two retinal landmarks that are easy to see. These may be vessel bifurcations or features of the retinal lesions. Two landmarks are chosen so that at least one will be visible even if the patient makes eye movements away from primary gaze (Fig. 1, left and center). The x and y coordinates of the landmarks are saved. There are two buttons on the mouse, and each corresponds to one landmark. Changes in the landmark coordinates from eye movement, as reflected by a cursor positioned on the landmark, will be used during the testing to correct stimulus placement for eye movement (Fig. 1).

3. **Choosing the testing pattern.** The investigator then selects the testing strategy. The program uses a circular grid of points (12 meridia, with points 1° apart radially) (Fig. 2) or a rectangular grid (Fig. 3); for both, the investigator can specify the location and the size of the grid to be tested and can add additional points. The testing pattern is visualized directly on the frozen fundus image so the investigator can determine that the intended retinal positions will be tested.

4. **Adding retinal sites of special interest to the preplanned sites.** Points can be added to the testing pattern. Alternatively, the investigator can make a fully custom-designed plan.

5. **Saving the testing plan and randomizing the order of stimulus presentation.** The coordinates of the landmarks and the planned stimulus points are saved in a file. The order for presenting the stimulus points is randomized. The same testing plan can be used for additional testing at different stimulus intensities at the same session. It can be used for future sessions as well, so that identical points are compared between sessions.
Landmark-Driven Testing. This portion of the procedure ensures that the desired retinal locations are tested, even if there is large eye movement, as depicted in Figure 1.

1. Returning to real time viewing of the fundus image. The patient is again instructed to fixate the cross.

2. Specifying the new position of a landmark. The operator positions a cursor over one of the specified retinal landmarks and presses a button when the cursor is correctly positioned. The new x and y coordinates of the landmark are noted by the computer. The change in location of the land-
mark signals that an eye movement has occurred and that a correction of the stimulus location must be made.

3. **Presenting the stimulus.** The computer then presents the first stimulus, at a location corrected for any change in landmark location. (The stimulus used is a square of length 10 minutes [5 pixels], presented for a duration of 400 msec.) Thus, the stimulus is presented in the correct retinal position even if the eye has made large eye movements.

4. **Patient response.** If the patient sees the stimulus, he or she presses a button. The response for the stimulus is recorded by the computer.

5. **Repeat steps 2 (or 1 if necessary) to 4 for each point to be tested.** Each stimulus presentation occurs in the same way, driven by the operator specifying (by cursor) the location of the landmark. The operator can reject, and repeat, a stimulus presentation if there is excessive eye movement or any blinking during the flash.

6. **Display of data.** At the completion of testing, a final fundus image is grabbed. The operator identifies the location of the landmarks on this image. The data points are then displayed on the fundus image, with different symbols denoting whether or not the stimulus was seen at that point (Figs. 2, 3) (We can also view a preliminary display of the points that have been tested during the session itself.) A hard copy of this can be made with a videoprinter or with a video cassette recorder. The operator can see where the scotomas are on the retina. The operator can then specify additional points to be tested using landmark-driven testing or manual testing.
FIGURE 3. The scanning laser ophthalmoscope (SLO) computer display showing the results of testing using a rectangular grid for an eye with 20/167 visual acuity and central geographic atrophy, with unstable fixation near the nasal aspect of the atrophy. (A) The SLO computer display of the results of testing with a bright stimulus using the landmark-driven fundus perimetry technique. Symbols as in Figure 2. Here, the retinal landmark is the intersection of a retinal vessel with the disc, marked by the thin white cross. The fixation cross (thick white cross) is placed just nasal to the geographic atrophy. (The black cross is unseen by the patient.) The optic disc is mapped out as scotomatous, as is the area of geographic atrophy (with some points that were seen also plotted within the atrophy). (B) A drawing of the results of A. The area of geographic atrophy is shaded. Black circles show points that the patient indicated were detected, and white circles show points that were not seen. The retinal landmark (thin cross) and fixation cross are noted. (C) The black squares indicate the retinal locations that would have been tested if correction for eye movements was not made. These would be the points actually tested by a conventional perimetry technique that was attempting to map out a regular grid of stimuli. The patient often lost fixation during the testing, with the cross placed in the area of atrophy. As a result, no points would have tested the area of the optic disc. (D) The results that would be obtained if no correction for eye movement was made. Black circles show points that were detected, and white circles show points that were not seen. The operator would be unaware that the grid points did not fall on the desired retinal locations. The results would be mapped as though the stimuli fell on the retina in a regular grid, when in actuality the stimuli fell as in (C). No points actually would have tested the disc in C so that the disc grid points are registered as seeing. The shift in eye position caused many more points to fall in the area of atrophy, and these appear here as nonseeing points in clear retina.

7. Storage of data. The coordinates of the landmarks along with the coordinates of the points in the testing strategy and the corresponding patient responses are saved in a file.

8. Testing at different stimulus intensities. The same plan may be used to test at different stimulus intensities. We typically test with a maximal stimulus intensity to test for dense scotomas. Then we measure the threshold at three or four retinal points that appear normal, and we use the value obtained to repeat our landmark-driven testing and to plot a threshold map (relative scotoma map). The preplanned strategy allows the same retinal points to be tested for each stimulus intensity.

Subjects
The technique described here was developed for use in our 5-year, National Institutes of Health-funded, natural history study of age-related geographic atrophy of the retinal pigment epithelium, a form of advanced age-related macular degeneration. Geographic atrophy progresses slowly over time, sparing the fovea until late in the course of the disease. It often progresses from paracentral foci of atrophy to a horseshoe ring or atrophy surrounding a spared central island. At the endstage, the atrophy involves the foveal center as well. Sites of geographic atrophy have an absolute scotoma. We are studying the rate of spread of geographic atrophy and absolute scotoma over time, how the fovea becomes involved, and whether fundus features and visual function in specific retinal areas can predict the likelihood of these areas becoming involved by the atrophic process. It is critical for us to be able to measure visual function over the same retinal points each year, and this technique allows that. Inclusion criteria have been described. Tenets of the Declaration of Helsinki were followed. Written informed consent was obtained from all patients. Institutional Review Board committee approval was granted.

Fifty eyes with geographic atrophy and 17 eyes with other macular conditions (including choroidal neovascularization, Stargardt's disease, and macular holes) were tested between July 1993 and April 1994 with a preplanned landmark-driven strategy used for both a bright stimulus for testing for dense scotomas and a threshold stimulus for testing for relative scotomas. This allowed us a way of assessing reliability and reproducibility of the technique. All 67 eyes tested in this manner are included in the analysis. The eyes with geographic atrophy and eyes with other conditions are considered as one group because the results were similar for the two groups.

The median visual acuity for the eyes tested was 20/60 (range, 20/16 to 20/914). The median age of the patients was 77 years (range, 18 to 97 years). Fifty eyes were tested using a circular grid pattern (Fig. 2), with 12 meridia tested at each degree extending 5° eccentrically, for a total of 60 points, and additional points were added in 19 of these eyes. The remaining
17 eyes were tested with smaller circular grids or with rectangular or custom grids. The average number of points tested per eye was 57. Thirty-one right eyes and 36 left eyes were included. Forty of the eyes tested were from women, and 27 were from men.

RESULTS

This technique has been successful in identifying areas of scotoma and in correcting for eye movements. Figure 2 shows an eye with 20/500 visual acuity and fixation at the nasal border of a large area of central geographic atrophy (Fig. 2A) and the displays seen on the SLO monitor of the results of testing with a bright (Fig. 2B) and a dim (Fig. 2C) stimulus. Figure 3 shows perimetry results for an eye with 20/167 acuity, and the degree of error corrected for by the landmark-driven technique. This eye did not maintain fixation on the cross for most of the testing but moved so the cross fell in the area of scotomatus geographic atrophy. If no correction for eye movement had been made, the retinal points tested would have been in different retinal locations than in the planned grid (Fig. 3C). If the operator attributed the points to the regular grid (as one would do with conventional perimetry), results would show a seeing region at the optic disc and the scotoma from the atrophy projected onto the seeing retina (Fig. 3D). By using landmark-driven fundus perimetry, the scotomas of the disk and geographic atrophy are mapped appropriately (Figs. 3A, 3B).

Validating Experiments

The following studies of validity and reliability were performed on the data obtained from the subject population defined:

Comparison of the Results for the Bright and Threshold Stimuli. The data files for each patient were analyzed. For each retinal location tested, the responses were categorized as dense scotoma if neither the bright nor the threshold stimulus was seen, as seeing if both the bright and the threshold stimulus were seen, as a relative scotoma if the bright but not the threshold stimulus was seen, and as an inconsistent point if the bright stimulus was not seen but the threshold stimulus was seen. The inconsistent category would include false-positive results (the patient indicated the dim stimulus was seen when it was not) and false-negative results (the patient did not indicate that the bright stimulus was seen when it actually was). An example of our composite maps is given in Figure 2D.

To test the reliability of our measure, we looked at what percentage of points tested were inconsistent; that is, the patient responded that the dim stimulus but not the bright stimulus was seen. Figure 4 shows the distribution of percentages of inconsistent points within each eye. The median percentage of inconsistent points was 2.6%. Fifteen eyes (22%) had no inconsistent points, and 32 eyes (48%) had at most one inconsistent point. The median percentage of points with dense scotoma was 26% (range, 0% to 66%). When the eyes were divided into a consistent group (≤2.5% inconsistent points) and an inconsistent group (>2.5% inconsistent points), the inconsistent group had a significantly greater percentage of dense scotoma points (median 8% dense scotoma points for consistent group, 35% for inconsistent group, t-test, P < 0.001). The inconsistent group also had significantly lower visual acuity than the consistent group (mean LogMAR 0.40 (20/50) for consistent group, LogMAR 0.64 (20/87) for inconsistent group, t-test, P < 0.02), although there was overlap for each of these measures between the two groups. There was no significant age difference between the groups (t-test, P = 0.60).

Thus, there was on average a small number of inconsistent points, and a higher percentage of inconsistent points was associated with a higher percentage of dense scotoma points and a lower visual acuity. An evaluation of the location of the inconsistent points showed that 85% of these were adjacent to an area of dense scotoma, suggesting that a small eye movement could account for a stimulus seen at one time but not at another.

Comparison of the Perimetry Maps With the Location of Geographic Atrophy. For eyes with geographic atrophy, we compared how closely the areas of dense scotoma on the perimetry maps corresponded with the sites of geographic atrophy. During testing, our apparatus generates a map of the perimetry results superimposed properly on the fundus image. (Figs. 2, 3). Our SLO uses infrared light for imaging and gives
a fundus image that looks different from a fundus photograph. In the future, we will be making quantitative comparisons of the SLO image with the fundus photograph. For this study, one author (DH) reviewed the videotapes and hard copies of the images and drew the outline of the geographic atrophy as seen on the SLO onto a grid. Another author (JS) determined the number of dense, relative, seeing, and inconsistent points that fell in atrophic and nonatrophic regions. Ninety-five percent of all dense scotoma points fell within or on the border of areas of atrophy. In addition, an average of 3 relative scotoma points and 0.5 seeing points per patient fell in the observed areas of atrophy. Fifty-three percent of all inconsistent points fell in areas of atrophy, and another 30% fell near the borders of atrophy. Thus, there is good agreement between the location of dense scotoma points and the sites of geographic atrophy in the SLO image.

Amount of Eye Movement Corrected by the Landmark-Driven Technique. We were interested in evaluating whether we were reducing the error in position of the stimulus on the retina using our technique. For this reason, beginning in February 1994, we saved the location of the landmark cursor for each stimulus presentation as a measure of eye movement. The location of the cursor at the time the stimulus is presented is a significant underestimate of the total amount of eye movement because the operator often waits until the eye has returned to near the original position before triggering the stimulus. Assuming the cursor was placed accurately (see Accuracy of Cursor Placement on the Landmark), the distribution of the cursor positions about the landmark gives us a measure of eye movement and the minimum amount of error in position that would be made if no correction had been made. These data were saved for 20 eyes. The average deviation of the landmark position from the original position for each stimulus presentation was 71 minutes (355 μm), with eight eyes having average deviations > 80 minutes (400 μm). There was a significant (r = 0.71) direct correlation between the amount of eye position change and the logMAR visual acuity; eyes with poor visual acuity tended to have larger changes in eye position (Fig. 5). The standard deviation of the eye position change in each eye also is shown (Fig. 5), and it increased with increased mean eye position change. This means that the amount of position change for one stimulus presentation may vary greatly from that of the next.

For the eye in Figure 3 with visual acuity of 20/167 and unstable fixation, the average change in landmark location per stimulus presentation was 58 minutes (290 μm). The eye movements were largely corrected by the landmark-based fundus perimeter technique; hence, the errors in perimetry mapping shown in Figures 3C and 3D did not occur.

Accuracy of Cursor Placement on the Landmark. Our technique assumes that the operator can place the cursor on the landmark accurately in real time. To test this, we reviewed the videotapes of the testing session for the subjects. Fifty-one of the testing sessions had been taped. For each eye, we randomly selected frames showing five different placements of the cursor over the landmark. For each grabbed frame, we noted the coordinates of the landmark and the coordinates of the cursor that was to have been placed on it. We computed the error in cursor placement. Overall, there was an average difference in x position of −0.70 minutes and an average difference in y position of −0.10 minutes, so there was negligible systematic bias in cursor placement. When the absolute magnitudes of the distance (square root of [x squared plus y squared]) between the cursor and the landmark were averaged, there was a median absolute deviation of 20 minutes (4 pixels, or 100 μm). (This is greater than the variability that could be accounted for by digitization of the image into pixels.) Some of this error is accounted for by decreased resolution in the image when testing certain patients or by the choice of a landmark imperfectly demarcated, such as having difficulty seeing where to locate a vessel bifurcation. This may be an easier task on a newer model SLO because landmarks can be seen more clearly.

Absence of Significant Rotation or Magnification Changes. Our technique assumes that the location of a single landmark is sufficient to determine the location of other points in the retinal image. This is true if there is only linear translation (i.e., movement of the eye in the x and y directions), without appreciable rotation of the eye or change in magnification (be-
As noted above, we think this technique is a rapid one. To validate this, we measured the time taken to perform the different steps of the procedure for the first seven of the patients whose videos we evaluated as described. This testing took place in the early months of this study, and the operator was not trying to test rapidly. The time to align the patient, to set up the testing strategy, and to describe the test took <2.5 minutes for all patients, with most requiring 1.5 minutes or less. The time for testing 60 preplanned points at one stimulus intensity took from 1.5 to 3.7 minutes. This depended primarily on the rate at which the operator triggered the stimulus presentation, and it varied depending on eye movement and rapidity of patient response. Approximately 2 minutes of testing were required to establish the threshold level for the test for relative scotomas. The testing strategy was repeated with the threshold stimulus intensity. The final results generally were displayed within 30 seconds of test completion. Thus, for patients such as these, the testing of each eye with two stimulus intensities should take no more than 10 to 15 minutes. The technique was easy to administer to elderly patients, and separate testing has shown the technique to be simple for children to perform.

**DISCUSSION**

Our landmark-driven fundus perimetry technique allows for accurate testing not subject to the potential errors described. We use a technique of red light flashes to ascertain the location of the stimulus without having to correct for reaction time. We drive the testing of each point by indicating the position of a retinal landmark, such as a vessel bifurcation. This allows us to test the desired points no matter where fixation is. It allows for an automatic summary of the data on a fundus image without a laborious videotape data analysis. It randomizes the points tested so that stimulus position uncertainty is present. It can discourage testing of narrowly defined retinal regions to the exclusion of other regions (although custom testing can often take the form of a high density of stimulus points in certain locations and fewer points in locations of less interest). Testing is much more rapid by this method; the investigator need only make one cursor selection rather than specify the point to be tested and the landmark location for each trial. Contrary to when registration is performed after stimulus presentation, we have not found that we inadvertently failed to test in areas of interest. Additionally, the same preplanned strategy for a given patient can be used from year to year and, if the points are defined relative to a constant retinal landmark, the same retinal locations will be tested even if fixation changes.

There is an intrinsic limitation to the accurate localization of the stimulus on the retina. The specification of the retinal location at the instant before testing obviously does not guarantee that the eye does not move during the stimulus presentation. As small as we make the stimuli, there remains uncertainty in the stimulus location during presentation because of small eye movements during the presentation. However, a recent study of fixation stability in low vision patients during perimetry with the SLO showed that during a 400-msec flash (our normal duration), >50% of trials measured had a shift of no more than 15 minutes of visual angle (75 μm). Eighty-five percent had shifts of no more than 1.5° (450 μm). In contrast, when stimulus duration was 1000 msec, <10% had a shift of 15 minutes of visual angle or smaller, whereas 40% had shifts of 1.5° or more. Thus, movement after stimulus presentation tends to have a longer latency than our stimulus duration. This points to an additional advantage of our landmark-driven fundus perimetry technique over the manual technique, which grabs an image at the end of stimulus presentation to use for registration and localization of the stimulus on a final retinal image.

In addition, the landmark-driven technique has the potential to drive a fully automatic technique with future improved and rapid pattern recognition by
Landmark-Driven SLO Fundus Perimetry

computer. Using currently available technology, it is possible to measure eye movements in real time. A computer can rapidly analyze eye position by determining if a landmark has moved more than some criterion distance during any stimulus presentation; the computer could then direct the SLO to retest a given point if the eye deviated more than the criterion distance from its initial position. In the future, it will be possible to perform real-time analysis and stabilization of a stimulus on the retina by a method similar to landmark-driven fundus perimetry. The investigator will be able to specify the points for desired testing by this method and will be able to identify two retinal landmarks for registration, or the computer will be able to select identifiable landmarks. During testing, the computer will be able to locate the landmark and present each point based on this localization without intervention by the investigator.

There are three major strengths of our technique. First, it can compensate for large eye movements. Second, it can present a regular pattern of points in random order and have the correct retinal locations tested without having to return and retest if the desired location was missed. Third, it is repeatable over long time intervals even if fixation changes in the interim because constant landmarks, such as vessel bifurcations, can be used. This allows for following visual function longitudinally over time at specified retinal locations.

Key Words

age-related macular degeneration, macular degeneration, perimetry, retinal locus for fixation, scanning laser ophthalmoscope, visual field

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