Reading With a Macular Scotoma

I. Retinal Location of Scotoma and Fixation Area

George T. Timberlake, Martin A. Mainster,* Eli Peli,† Reed A. Augliere, Edward A. Essock, and Lawrence E. Arend

To investigate how patients with macular scotomas use residual functional retinal areas to inspect visual detail, a scanning laser ophthalmoscope (SLO) was used to map the retinal locations of scotomas and areas used to fixate. Three patients with dense macular scotomas of at least 20 months duration and with no explicit low vision training were tested. SLO stimuli were produced by computer modulation of the scanned laser beam, and could be placed on known retinal loci by direct observation of the retina on a television monitor. Videotaped SLO images were analyzed to produce retinal maps that are corrected for shifts of stimulus position due to fixational eye movement, thus showing the true retinal locations of scotomas and fixation loci. Major findings were as follows: 1) each patient used a single, idiosyncratic retinal area, immediately adjacent to the scotoma to fixate, and did not attempt to use the nonfunctional foveola, 2) fixation stability with the eccentric fixation locus was as good as, or better than, that of ocularly normal subjects trying to fixate at comparable eccentricities, 3) fixation stability was not systematically related to clinical visual acuity, and 4) there is good agreement as to the shape and overall size of SLO and standard clinical tangent screen scotoma maps for these three patients. Invest Ophthalmol Vis Sci 27:1137-1147, 1986

The loss or reduction of reading ability produced by macular scotomas is widespread. In the United States, aging macular degeneration alone accounts for about 13% of registrations as blind,[1] and other common retinal diseases, such as diabetic maculopathy, can also produce dense central scotomas. Elimination of foveal function permanently by macular scotomas,[2,3] or temporarily by artificial means,[4] can reduce a normal reading rate of hundreds of words per minute to a few words per minute. Some patients with permanent macular scotomas never recover the ability to read.

The lack of basic information concerning residual functional retina and its actual use by patients with macular scotomas has hindered progress in visual and reading rehabilitation. Many patients with macular scotomas do learn to read (albeit slowly) with the aid of optical or electronic magnifiers, suggesting that they may place magnified text on a new, non-foveal retinal area and scan the text with this "pseudo-fovea." Little is known about the presumed pseudo-fovea, however, and many fundamental questions remain unanswered. Among these are the following: Is a single retinal area (pseudo-fovea) used to perform different visual tasks, such as fixation and reading, or are different retinal areas used depending on the visual requirements? What is the retinal position of a patient's pseudo-fovea and scotoma, and does the scotoma obscure text during reading? Does a patient "select" a pseudo-fovea on the basis of its retinographic characteristics, such as proximity to the nonfunctional foveola or the scotoma? Does a patient "select" a functionally optimal retinal area to scan text (i.e., does the pseudo-fovea have the best visual characteristics for text recognition)? Can a more effective area be identified and the patient taught to use it?

The purpose of our study was to develop and apply methods for answering these questions. We present here techniques for mapping the retinal location of macular scotomas and for determining the retinal loci that patients use to fixate small targets. In a subsequent report, we will present methods for determining the retinal loci that a patient uses to inspect acuity targets and to scan simple text. We used a scanning laser ophthal-

From the Physiological Optics-Psychophysics Unit, Eye Research Institute of Retina Foundation, and Department of Ophthalmology, Harvard Medical School, Boston, Massachusetts.

* Present address, Department of Ophthalmology, University of Kansas Medical School, Kansas City, Kansas.

† Also with Department of Ophthalmology, Tufts University School of Medicine, Boston, Massachusetts.

Presented in part at the Association for Research in Vision and Ophthalmology annual meeting, Sarasota, Florida, 1984.

Supported by NEI grant EY03966 (GTT).

Submitted for publication: October 2, 1985.

Reprint requests: Dr. G. T. Timberlake, Eye Research Institute, 20 Staniford St., Boston, MA 02114.

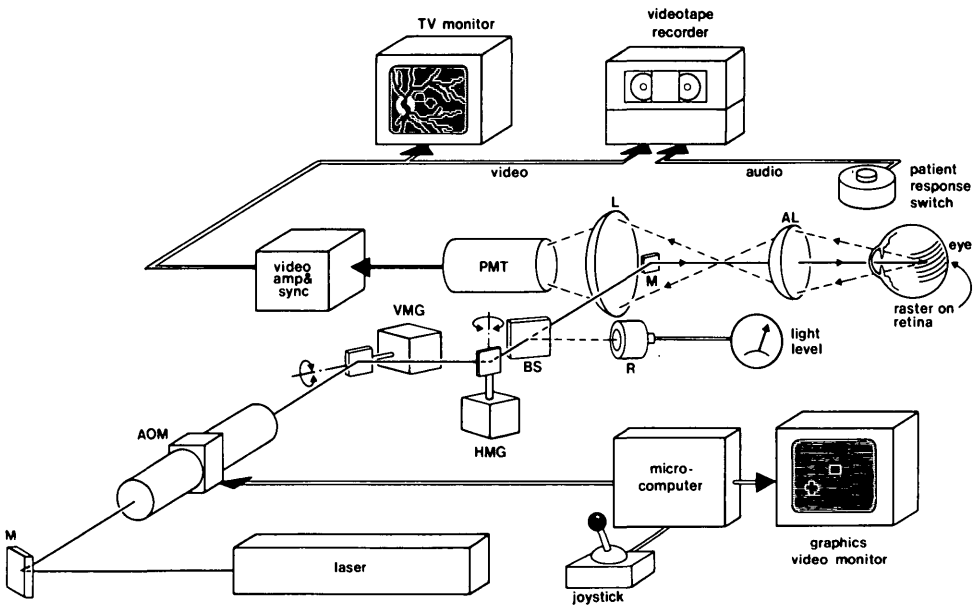

Fig. 1. Schematic illustration of the SLO. Single solid lines, laser-beam retinal illumination path. Dashed lines, light collection path. Double lines, electrical connections. AOM = acoustooptic modulator, VMG = vertical-scan mirror galvanometer, HMG = horizontal-scan mirror galvanometer, BS = beam splitter, R = radiometer, M = mirror, AL = aspheric lens, L = lens, PMT = photomultiplier tube.

moscope (SLO)[5,6] because a wide variety of visual stimuli may be produced on a patient's retina at light levels that are within normal environmental limits and safe for continuous exposure, and an investigator may view and document the location of the stimuli on the patient's retina. In addition, we compared scotoma maps made with the new SLO technique to conventional, clinical tangent-screen visual fields.

Materials and Methods

We used an SLO that was substantially improved over the instrument used previously to demonstrate the feasibility of mapping the retinal location of scotomas.[7] In addition, the present studies required development of computerized SLO image-analysis techniques that allow extensive analyses not practicable with the original[7] photographic method.

Scanning Laser Ophthalmoscope

Relevant features of the SLO are presented in Figure 1. (More detailed descriptions of SLO optical principles may be found in previous reports.[5,8]) The SLO has two major optical paths, one for producing a laser-beam raster on the retina and another for collecting light reflected from the retina.

Raster path: Yellow krypton laser light (568.2 nm) enters an acoustooptic modulator (AOM) controlled by a microcomputer (Apple II, Cupertino, CA). The intensity-modulated (first order) beam from the AOM is swept vertically in a 60 Hz sawtooth waveform by a mirror mounted on a galvanometer (VMG). A second mirror, mounted on a tuned-resonant galvanometer (HMG), sweeps the beam horizontally at 7,875 Hz with a sinusoidal waveform. The scanned beam is then reflected by a small mirror (M) optically conjugate with the eye's pupil and brought to focus on the retina by an aspheric, ophthalmoscopic lens (AL). The entry pupil of the laser beam in the eye's pupil is approximately 1 mm in diameter. The vertical and horizontal sweeps of the beam by the mirror-galvanometers produce a raster pattern of parallel horizontal lines on the retina.

Yellow (568.2 nm) krypton laser light is used because it is near a peak in the absorption spectrum of hemoglobin. It therefore provides an excellent image of the retinal vasculature, essential for providing the coordinate system for locating stimuli on the retina.

Light collection path: Light reflected from the retina is collected by the AL and an auxiliary lens (L) that images the pupil of the eye on the photocathode of a photomultiplier tube (PMT). Thus, all light exiting the pupil is used to form the image of the retina. Signals from the photomultiplier tube are amplified and synchronized with those driving the mirror galvanometers to produce video output that is simultaneously displayed on a video monitor and recorded on half-inch videocassettes. As the laser beam sweeps across the retina, the electron beam in the video monitor sweeps in synchrony across the screen. At each moment, the brightness of the spot produced by the electron beam is proportional to the amount of light reflected from the retinal point illuminated at that time. In this way, an image of the retina is constructed point-by-point on the video monitor.

Video output: As the laser beam is scanned horizontally at 7,875 Hz, it is also scanned vertically for 1/60 sec by the VMG. Thus, in each 1/60th sec, 131.25 laser lines are "drawn" on the retina (1/60 × 7,875). The

line is drawn in only one direction of the sinusoidal scan; the other direction (retrace) is blanked by the AOM. A video "field" containing 131.25 lines is generated and recorded on videotape every 1/60th sec. This is half the number of raster lines in a standard, RS-170, video field, and is necessary because tuned resonant scanners of 15,750 Hz (twice the frequency of ours) were not available. Thus, each tape-recorded SLO video frame (two fields) displayed 262.5 raster lines.

Light levels: The small illumination entrance pupil (1 mm in the plane of the patient's pupil) and the large-light collection aperture (the entire pupil) result in excellent light efficiency of the SLO,[8] and permit formation of an image of the retina at light levels well below those of indirect ophthalmoscopes or fundus cameras.[9] Since our krypton laser can produce approximately 0.2 W at 568.2 nm, the patient is protected from possible hazardous retinal irradiances in the following way. Raster power (Watts) is continuously monitored using the beam splitter (BS) and radiometer (R) shown in Figure 1. Retinal irradiance (Watts/cm^2), determined by calculating the retinal area of the raster, is maintained at less than 10^{-4} W/cm^2, the ANSI Z-136.1 maximum permissible retinal irradiance for continuous exposure to 568.2 nm light.[9] In practice, retinal irradiance never exceeded 0.5×10^{-4} W/cm^2, one-half the maximum permissible power density. If the laser beam is not scanned fully, it is blocked automatically by a shutter, since a smaller raster would increase retinal irradiance above maximum permissible levels.

Raster graphics: The microcomputer produces test stimuli in the laser-beam raster that are made up of picture elements, or "pixels." One pixel is generated when the computer causes the AOM to turn the laser beam off briefly. A single pixel appears as a small black dot in the raster. A total of 280 pixels can be produced in each raster line, and 192 lines can be modulated by the Apple computer to produce a graphic image as large as 280×192 pixels. Since only 131.25 laser raster lines are produced in each field, two fields are needed to represent the entire 192 vertical pixels, and the graphic image is displayed in alternate fields (i.e., 96 alternate lines were displayed in the first field, and 96 interlaced lines in the second field). The bottom 70 lines of the laser raster do not contain any graphics. Any graphic image that can be made by the computer and displayed on its video monitor can also be generated in the laser-beam raster. The angular subtense of each pixel depends on the overall raster size. In our SLO, raster size was continuously variable from 30° on a side to 12° on a side, and was adjusted to produce pixels of 7–3 min on a side.

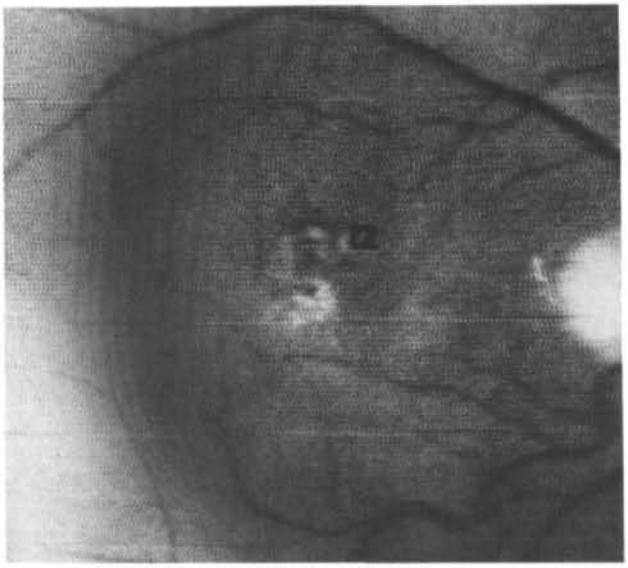

Fig. 2. SLO video frame showing the fixation stimulus (dark square with a bright center) on Patient 1's retina (OD) when she was asked to "look at" the bright center and press a switch when doing so. Foveolar position is down and to the left of the fixation stimulus. The frame shows pigment clumping and RPE atrophy from exudative aging macular degeneration and macular photocoagulation. All SLO images presented here have been electronically rotated so that the image represents a projection of the retina onto the patient's visual field (i.e., retinal directions in the figures correspond to visual directions for the patient).

Procedure

After SLO testing procedures and purposes were carefully explained to the patient and informed consent was obtained, the pupil of the eye to be tested was dilated with 1% tropicamide (Mydriacyl; Alcon Laboratories, Fort Worth, TX). The patient sat in front of the SLO and steadied her head on a chin and forehead rest that could be positioned by means of a mechanical joystick. The eye was then aligned so that the narrowest portion of the scanned beam (1 mm in diameter) was in the plane of the pupil, and small adjustments in position were made to produce the optimal image of the retina on the video monitor. Alignment of the eye in the laser beam was readjusted throughout the session whenever head movement misaligned the laser beam and degraded the video image.

Fixation: The retinal fixation locus was determined using a square, black target (42×42 min) with a bright center (14×14 min) in the center of the SLO raster (Fig. 2). At the beginning of the first experimental session, the patient was asked to "look at the bright center of the dark square just as if you were trying to look at a small, far-away object." Patients were instructed to press a switch that treated an audible tone when they were "looking right at the center of the target" and to release the switch if fixation were lost. The experi-

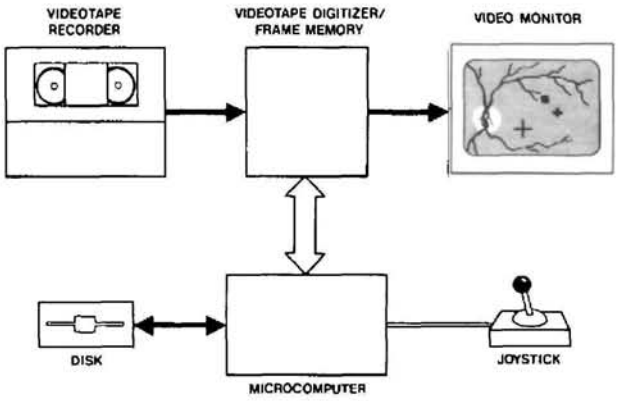

Fig. 3. Schematic of instrumentation used to analyze SLO video frames. Individual videotaped SLO images were digitized and stored in digital memory. A microcomputer and joystick allowed positioning of a cursor in the displayed video image. The cursor was placed on blood vessels and stimuli and their cartesian coordinates were stored on magnetic disk.

menter counted aloud a 5 sec fixation trial, at the end of which the patient was asked to blink and rest briefly. Five such trials were recorded on videotape along with the tone that indicated the patient was fixating the target.

Scotoma mapping: The patient fixated a cross-shaped target in the SLO raster, and the microcomputer generated a small, square mapping stimulus. The patient was asked to press a switch that produced an audible tone whenever the mapping stimulus became visible.

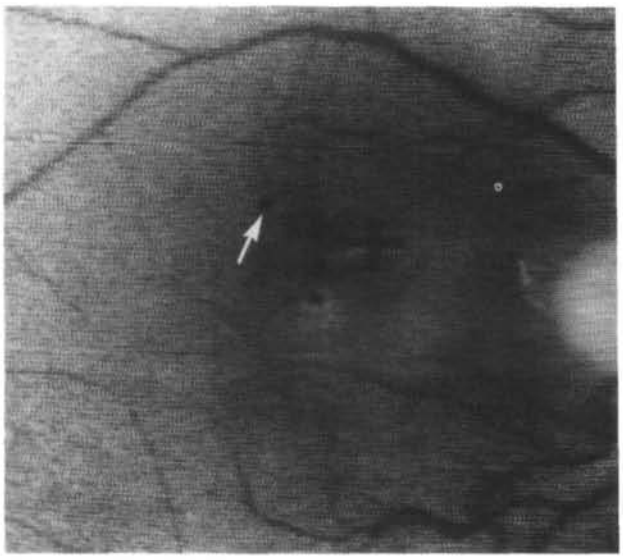

Fig. 4. Digitized SLO video frame illustrating the scotoma mapping procedure. Frame digitization and storage were initiated automatically by a videotaped signal indicating that the patient had pressed a switch when the stimulus first became visible. The 14 × 14-min arc mapping stimulus (dark square indicated by arrow) is seen at 10 o'clock relative to the cross-shaped fixation stimulus and shows the retinal location at which the stimulus was first seen by the patient.

The approximate location of the scotoma was determined by moving the stimulus about on the retina by means of a joystick (connected to the computer) to determine where the stimulus was not seen by the patient. Once the approximate location of the scotoma was found, the stimulus was positioned in its center and then moved radially outward at constant velocity (2°/sec) by the computer. When the stimulus became visible, the patient pressed a switch that recorded a tone on the audio channel of the videotape recorder that was continuously recording SLO video images. The mapping stimulus stopped as soon as the patient pressed the switch, remaining in position for 0.5 sec before automatically returning to the starting position inside the scotoma. When the patient was ready, a new trial began and the mapping stimulus moved radially outward along a different meridian. This sequence continued until 36 different meridians were tested in pseudo-random order to map the scotoma densely. The mapping stimulus was dark on a bright background (the laser raster), and had a contrast of close to 100% since it was created by turning the laser beam off. Mapping stimulus sizes of 14 and 28 min arc (2 × 2 and 4 × 4 pixels) on a side were used.

Video Data Analysis

Videotaped SLO images showing the retinal positions of mapping stimuli were analyzed to produce a retinal scotoma map using the system shown schematically in Figure 3. As the videotape was replayed, the recorded tone indicating that the mapping stimulus had become visible (i.e., the patient pressed the switch), causing the current video frame to be digitized and stored in a video frame memory. The videotape was stopped and the digitized frame displayed on a video monitor (Fig. 4). A microcomputer (Apple II, Cupertino, CA) interfaced to the video frame memory generated a cross-shaped cursor that could be positioned by means of a joystick to any location within the digitized image. The cursor was positioned, in turn, on each of four preselected blood vessel branchings or intersections and on the stimulus. The cartesian coordinates of the vessels and stimulus were then recorded on magnetic disk. Each of the videotaped scotoma mapping trials was analyzed in this fashion. Three to four hours were required to evaluate each set of 36 trials at each stimulus size. Trials were rejected from analysis if saccades during the trial shifted the mapping stimulus to retinal areas where it was immediately reported visible by the patient.

The retinal position of fixation stimuli was also measured using the same preselected blood vessel landmarks. Three or four video frames at 0.5–1 sec intervals were selected from each 5-sec fixation trial.

A total of 18 fixation stimulus positions were measured for each patient.

Measurements of vessel landmarks and stimulus position were repeatable to within 1 pixel and, since resolution in the digitized, displayed video frames was approximately 4 min/pixel, measurements were reliable to within 4 min.

The measurements of vessel landmarks and stimulus position described above establish the location of the stimulus relative to a retinal coordinate system (i.e., the retinal blood vessels). In principle, only one vessel landmark is needed to establish the retinal location of the stimulus, but at least one additional landmark was required to correct for image magnification changes due to slight changes in the size of the laser-beam raster caused by electronic instabilities. To correct for these magnification changes, horizontal and vertical distances between two vessel landmarks common to every analyzed video frame were used to calculate a magnification correction factor for each digitized image. Four vessel landmarks were pre-selected for measurement, because one or two of them frequently could not be seen in digitized frames due to small ocular media opacities or vignetting caused by misalignment of the eye in the laser beam. In addition, the horizontal raster scan sinusoidally distorted the SLO image, and at least two vessel landmarks were required to correct for this distortion.

Fixational eye movements shift the video image of the retina, and thus, measured vessel coordinates differ from frame to frame. To create a composite retinal scotoma map showing the true retinal location of the mapping stimulus when it first became visible to the patient on every trial, it was necessary to compensate for these retinal shifts. To do so, a single video frame of the retina (the "master" frame) is digitized and displayed. The predetermined blood vessel coordinates are then measured and the cartesian coordinates of the analyzed frames are recalled by the computer. After correction for magnification changes and sinusoidal distortion of the image (noted above), blood vessel coordinates on the analyzed frames are then computationally shifted to correspond to the same vessels in the displayed master frame. This results in the stimulus positions on the analyzed frame being shifted to the correct retinal position on the displayed, master frame where it is plotted by the computer. In effect, this procedure corrects for shifts of the retinal image of the stimulus produced by eye movements during testing and displays the true retinal location of the scotoma.

Patients

Patient 1: A 61-year-old woman with exudative macular degeneration in both eyes had experienced a subretinal hemorrhage in her amblyopic left eye 4 yr prior to our testing. Visual acuity in her left eye was 20/300, and she stated that she used her right eye exclusively for reading. All SLO testing was performed on her right eye. She first experienced a "blind spot" in her right eye 29 months before our tests, and was noted to have exudative, aging macular degeneration. The choroidal neovascularization in her right eye was successfully treated by argon green laser photocoagulation 20 months prior to SLO testing. Visual acuity in her right eye was stable at the 20/50 level at the time of the tests.

Patient 2: This 36-year-old woman received a blow to her left eye from a blunt object 31 months prior to SLO testing and experienced immediate loss of central vision in her left eye. She was noted to have a traumatic macular scar with relatively inactive choroidal neovascularization. The dense central scotoma in her left eye was first documented 28 months before our tests. Visual acuity in her left eye fluctuated from 20/50 to 20/400 over the 28 month period. At the time of SLO testing of the left eye, acuity was 20/300 and stable. Acuity in her normal right eye was 20/20.

Patient 3: Geographical aging macular degeneration in both eyes was diagnosed 9 yr before SLO testing in this 73-year-old woman. At the time of testing, her right eye had 20/200 visual acuity and a dense central scotoma. Her left eye, the subject of SLO testing, had 20/25 visual acuity and a dense central scotoma first documented 20 months prior to SLO testing, although she had noted visual loss in this eye 1 yr previously. This patient reported using her left eye exclusively for reading.

Results

Composite retinal maps showing the retinal locations of scotomas and fixation areas are shown in Figures 5–7. Standard clinical tangent-screen central visual fields performed on the same date as our tests are shown for comparison. The SLO images of the retina shown in the figures were reversed electronically so that they are equivalent to a projection of the retina onto the visual field. We found this format to be extremely useful during testing and analysis (unlike the standard, ophthalmoscopic format) since directions on the video image of the retina corresponded to visual directions for the patient. For example, with our format, a stimulus moving "up and to the right" on the video display of the retina appeared to move "up and to the right" to the patient. Were the standard ophthalmoscopic format used, movement of a stimulus in the patient's "up and to the right" direction would require movement "down and to the left" on the video monitor. This reversal proved to be cumbersome and prone to

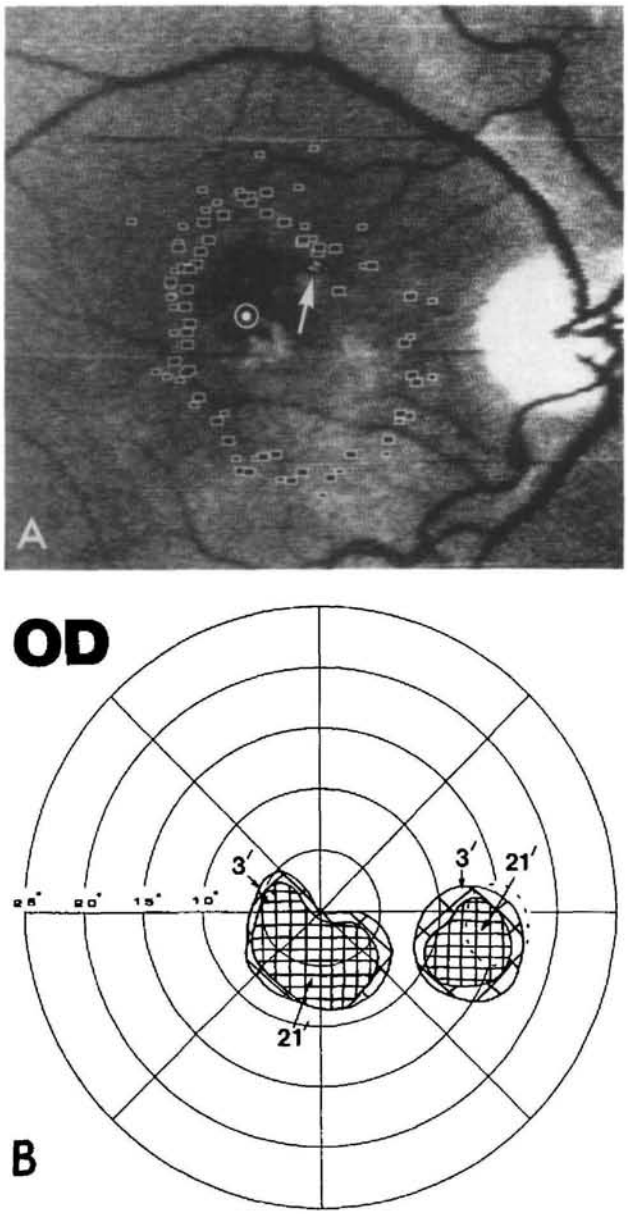

Fig. 5. A, Computer-generated SLO retinal map showing the retinal locations of the scotoma and the area used to fixate by Patient 1 (right eye). *Scotoma.* White/black squares show the retinal locations at which the mapping stimulus became visible to the patient on each radial traversal from the scotoma center. Larger white/black squares represent a 28 × 28-min arc stimulus; smaller white/black squares a 14 × 14-min arc stimulus. *Fixation area.* The retinal area used to fixate is shown by solid black squares each with a white dot in its center (indicated by arrow). Eighteen individual fixations are plotted. Estimated foveolar position is shown by a circular white dot and ring, photographically superimposed on the photograph. B, Clinical, tangent-screen central visual field (Bausch and Lomb, Rochester, NY; "Autoplot") of patient 1's right eye made on the same day as SLO measurements. Dense crosshatching indicates scotoma mapped with a 21-min arc (21′) diameter stimulus. Less dense crosshatching indicates scotoma mapped with 3-min arc (3′) diameter stimulus. Physiologic scotoma (optic disk) is seen to the right.

errors. In this report, we will refer to retinal directions in terms of left, down, up, and right corresponding to the patient's visual direction. Anatomical directions are as follows: 1) inferior retina is at the top of each photograph, and 2) nasal retina is on the side of the optic disc.

Comparison of SLO and Tangent-Screen Fields

There is good agreement between the shape of the SLO scotoma map and the standard tangent-screen map for each patient (cf. the two panels of Figs. 5–7). In addition, the two isopters mapped for patients 1 and

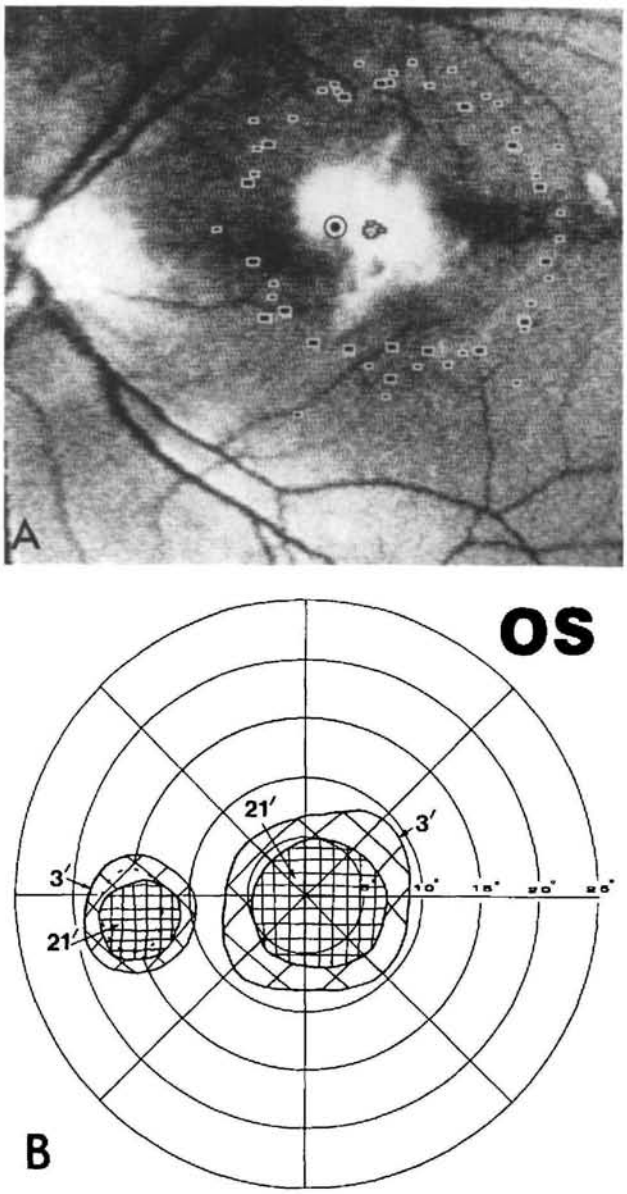

Fig. 6. A, SLO retinal map for Patient 2's left eye with a traumatic macular scar. *Scotoma.* Scotoma mapping stimulus sizes are as in Figure 5A. The scotoma encircles a prominent macular scar (white area). *Fixation area.* Eighteen individual fixations are plotted as small black squares with a white dot. These are seen roughly in the scotoma center on the macular scar. Estimated foveolar position is indicated by the circular dot and ring. B, Clinical, tangent-screen central visual field for the same eye. Scotoma mapping stimulus sizes are indicated as in Figure 5B.

2 (Figs. 5, 6) have the same relationship as in the tangent-screen fields. The SLO scotoma maps, however, were larger in diameter than those found by tangent-screen perimetry. These similarities and differences are summarized below.

Patient 1: Both the SLO map and the tangent-screen fields (Fig. 5) revealed a dense, kidney-shaped scotoma with the concave side facing up and to the right. The two isopters mapped with the SLO are similar to those found with tangent-screen perimetry. For example, the 14-min arc stimuli seen in the SLO map are radially farther out at the top and right sides of the scotoma, but are congruent with the 28-min arc map at the bottom and left. This is similar to the tangent-screen map, although differences in the two SLO isopters are less pronounced than those in the tangent-screen field. The largest vertical extent of the scotoma measured with the 28-min arc SLO stimulus and the 21-min arc tangent-screen stimulus was 13.7 and 10.6 deg, respectively. Thus, the SLO map was approximately 30% larger than the tangent-screen map.

Patient 2: A large, dense, almost circular scotoma enclosed the macular scar (Fig. 6). The same overall shape is seen in the tangent-screen field. There is little difference in the isopters mapped with the 28- and 14-min arc SLO stimuli, although the smaller stimuli did tend to be seen at positions radially farther outward from the scotoma center. The diameter of the scotoma as mapped with the 28-min arc stimulus was 14.6° along the vertical axis, approximately 25% larger than the 21-min arc tangent-screen scotoma, which was 10.9°. The SLO scotoma correlated well, with observable but subtle fundus defects seen during mapping (these are observable on the SLO monitor, but not in the tape-recorded, digitized images). For example, for this patient, an ophthalmoscopically apparent circular line surrounded the fibrous scar, delimiting the maximal extent of exudates from choroidal neovascularization. When the mapping stimulus reached this line, the patient immediately reported that it was visible.

Patient 3: The SLO scotoma map (Fig. 7A) shows two macular scotomas, which are contiguous in the foveolar region. Again, there is excellent agreement between the SLO map and tangent-screen fields as to the overall shapes of the scotomas. The largest vertical extent of the larger, upper scotoma in the SLO map was 10.3°, 3% larger than the 21-min arc tangent-screen map.

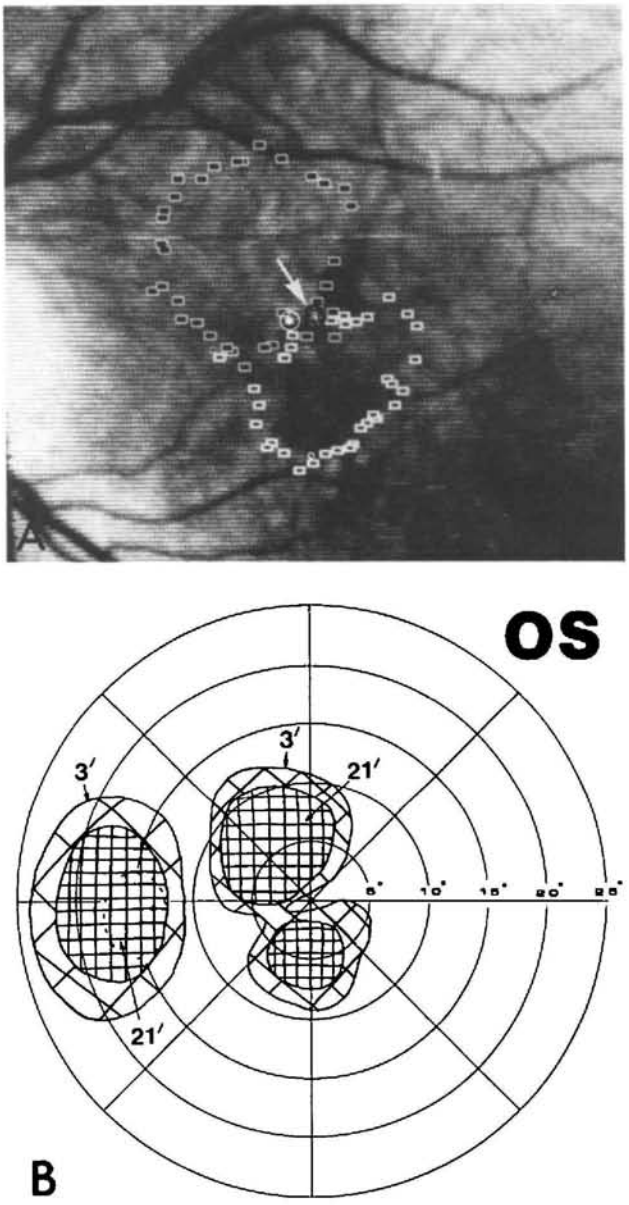

Fig. 7. A, SLO retinal plot for Patient 3's left eye with geographic aging maculopathy. *Scotoma.* Retinal positions at which the mapping stimulus became visible to the patient are indicated by white/black squares. Two contiguous scotomas were found: the lower scotoma is shown by the white/black squares with the smaller black center. Both scotomas were mapped with a single stimulus size, 28 × 28-min arc. *Fixation area.* The retinal position of the fixation area, indicated as in Figures 5–6, is seen as a black area (arrow) near the contiguous border of the two scotomas, to the right of the foveolar position (white dot and circle). **B,** Clinical, tangent-screen field for the same eye. Scotoma mapping stimuli are indicated as in Figures 5B, 6B.

Fixation Locus

The retinal area used for target fixation is indicated in each map by solid black squares with a white dot in the center. Each black square/dot shows the retinal position of the bright center of the fixation target during a single sampled video frame (see Materials and Methods). A dot with a circle around it (produced photographically) marks the foveolar position. We estimated foveolar position from high-quality, fundus photographs by fitting straight lines to retinal vessels that "point" toward the macular center and determining their area of intersection, and by measuring optic disc diameter and using anatomical measurements relating

Table 1. Fixation stability with eccentric fixation loci

Patient number	*Retinal eccentricity (deg)*	*BVA (min arc²)*	*Horizontal SD (min)*	*Vertical SD (min)*	*Clinical visual acuity*
1	3.8	623	10.3	8.6	20/50
2	1.5	507	9.0	8.0	20/300
3	1.1	584	7.4	11.1	20/25

BVA = bivariate area, SD = standard deviation.

foveolar position to disc diameter and position.[10] Both measures were in close agreement, and the circular dot marking foveolar position (approximately 0.9° in diameter) encloses both position estimates.

Two measures of fixation stability were calculated from the fixation data: 1) the horizontal and vertical standard deviations of target position, and 2) the bivariate contour ellipse area (BVA). The second statistic is analogous to a two-dimensional standard deviation and indicates the retinal area in square minutes of arc in which the fixation target center would be found 68.3% of the time.[11] Table 1 summarizes fixation stability measures, as well as eccentricity of the acuity locus and clinically measured visual acuity.

Patient 1 had a fixation locus that was immediately adjacent to the "kidney-shaped" macular scotoma on its convex side (Fig. 5A). Although the fixation locus appears to be slightly within the scotoma, this is an artifact of the kinetic perimetric technique used. Specifically, there is a reaction time between the time the stimulus became visible and the time the patient pressed the response switch. Since the stimulus travelled an additional radial distance during this period, the plotted size of the scotoma is larger than its actual size. For example, with a stimulus velocity of 2°/sec and a reaction time of 0.5 sec, the stimulus will travel an additional 1° beyond the edge of the scotoma. If all stimulus points are moved radially inward by 1°, the fixation locus would lie outside the plotted scotoma.

Patient 1's fixation area was visually up and to the right of the scotoma (Fig. 5A); thus, when this patient fixated a point, the scotoma was down and to the left of the point. The patient used only this retinal area to fixate stationary targets. When fixation targets were flashed on in random positions in the raster, she immediately placed them in this locus. Both the eccentricity of the fixation locus (3.8°) and the retinal area used to fixate (BVA: 623 min arc²) were the largest of the three patients tested. The fixation locus would have been closer to the foveolar position by approximately 1° if it were located adjacent to the scotoma at the 9 o'clock position (just outside the scotoma to the left of the foveola, as seen in Fig. 5A). Finally, the observed retinal fixation locus in the SLO map could be deduced approximately from the tangent-screen fields by noting that the scotoma ("blind spot") corresponding to the optic disk is shifted down and to the left while the patient fixated the center of the tangent screen.

Somewhat surprisingly, the fixation locus for Patient 2 (Fig. 6A) was found to be in the center of the dense circular scotoma on the macular scar, indicating a small central area of functional retina within the large scotoma. Attempts to map the border of this preserved area were unsuccessful. The existence of this central preserved area was not noted by the clinical perimetrist. The center of the fixation locus was visually to the right and slightly downward of the estimated foveolar position (eccentricity, 1.5°), but retinal distortion from scar formation makes it difficult to determine exact foveolar position. Fixation stability was the best of the three patients (BVA, 507 min arc²).

Although Patient 2 could fixate reasonably well, she had considerable difficulty in initial placement of the fixation target in the fixation locus. For example, when fixation targets were turned on in random positions outside the scotoma, the patient made a large saccade that moved the fixation locus toward the target. On most attempts, however, the saccade resulted in the target being placed in the annular scotoma, not on the fixation locus. The patient then used three discernable strategies in attempting to place the target in the fixation locus. First, small saccades were made, and one occasionally resulted in proper stimulus placement. Second, a large downward saccade was executed to place the stimulus visually above the scotoma, and a second large saccade made to place it in the fixation locus. Third, the patient blinked several times, placing the stimulus outside the scotoma, and another large saccade was made. Periods of as long as 20 sec were sometimes required for this patient to place the fixation stimulus in the fixation locus.

For Patient 3 (Fig. 7A), the fixation locus was nested near the common border of the two scotomas, 1.1° radially to the right and slightly above foveolar position. This location appears to be the closest possible location to the foveolar position outside the scotoma. When this patient fixated, the scotomas were visually to the left, above, and below the object fixated. Fixation stability was intermediate to the two other patients, with a BVA of 584 min arc².

Discussion

Comparison of SLO and Tangent-Screen Fields

The overall shapes of the macular scotomas mapped with the SLO agree quite well with those mapped by standard, clinical, tangent-screen perimetry. This similarity is striking in view of the substantial differences in stimulus conditions. For example, standard tangent-screen testing is performed with dim (mesopic) white-light background illumination, whereas the SLO back-

ground (the raster) is in the medium photopic range and is highly monochromatic (568.2 nm). Furthermore, standard tangent-screen stimuli are incrementally brighter than the background, whereas SLO stimuli are darker than background with contrasts close to 100%.

The two isopters mapped with the SLO show less separation than those found with tangent-screen perimetry. In part, this is because the difference in stimulus area was smaller for the two SLO stimuli than for the two tangent-screen stimuli. Specifically, the 28- and 14-min arc SLO stimuli had areas of 784 and 196 min arc^2, respectively (a ratio of 4:1), whereas the 21- and 3-min arc tangent-screen stimuli had areas of 334.3 and 9.3 min arc^2, respectively (a ratio of 36:1). Attempts to match the tangent-screen area ratio by using a 1 pixel (7-min arc) mapping stimulus in the SLO were unsuccessful because the 15 Hz raster flicker severely reduced target visibility.

Scotoma diameters found with the square SLO stimulus, 28-min arc on a side, were 3–30% larger than those measured with the circular, 21-min arc diameter tangent-screen stimulus. Since the area of the SLO stimulus was more than twice that of the tangent-screen stimulus, it might be expected that the scotoma diameter found with the SLO would be smaller than that found with the tangent-screen. This is certainly the case in standard perimetry when stimulus intensity is constant and only area is varied, as seen, for example, in the tangent-screen fields in Figures 5–7. Further, the much higher background illumination in the SLO should result in smaller scotoma diameters, since contrast sensitivity for small perimetric targets increases with background illumination.[12] Nevertheless, SLO scotoma diameters were larger than those found with tangent-screen perimetry. This difference might have arisen as a result of differences in stimulus velocity in the two techniques. In the SLO, stimulus velocity was a constant 2°/sec, whereas, in the tangent-screen technique, the stimulus is moved manually and velocity varies with examiner. If the clinical perimetrists used a stimulus velocity less than 2°/sec and patients' reaction times are the same in the two testing situations, tangent-screen testing would yield smaller scotoma diameters.

Unlike clinical, tangent-screen methods, we corrected for shifts in the retinal position of the stimulus due to fixational eye movements. In principle, lack of correction for eye movements in the tangent-screen technique should result in a mapped scotoma that has more jagged edges and differs in shape from the SLO-mapped scotoma (assuming a smoothly bounded scotoma). This did not occur for two reasons. First, tangent-screen perimetrists connected individually determined points along the scotoma map by smooth lines. Second, patients were selected who were cooperative and known to be able to perform clinical psychophysical tests well. This procedure apparently resulted in selection of patients who also fixate well (standard deviations of eye position were all less than 11-min arc). Thus, with this group of relatively good fixators, our correction procedure would produce only small differences in the scotoma map. With poorer fixators, there should be a pronounced difference in tangent-screen and SLO maps.

The overall similarity of the SLO and conventional clinical scotoma maps indicates that SLO findings may be applied directly to clinical practice. SLO maps also provide additional information of clinical significance. For example, it is possible to determine the retinal locations of the scotoma, the foveola, and active choroidal neovascularization. This is useful data because the laser surgeon wishes to avoid unnecessary damage to functional retinal loci during macular photocoagulation. In addition, knowledge of the sizes and retinal positions of scotomas should be useful in conventional low vision rehabilitation of patients with bilateral macular scotomas.

Fixation Locus

The most striking feature of the fixation loci is that they are immediately adjacent to the dense scotoma found with the 28-min arc stimulus. Patient 2's fixation locus was within the inner border of a ring-shaped scotoma. In view of the small size of the functional area inside the scotoma (we were unable to map it), the fixation locus must have been arbitrarily close to the annular scotoma's inner edge. Other instances of central preservation of function in macular disease have been reported by Hart and Burde, who found such relative central sparing in 20% of the cases of macular disease they studied.[13] We have found one other instance of central preservation, undetected by standard perimetry, in a patient with geographic aging macular degeneration.

A second important aspect of the fixation locus is its relationship to the foveolar position. It has sometimes been assumed that the fixation locus is as close as possible to the foveolar position.[14] This is true for Patients 2 and 3, but not for Patient 1. Furthermore, unlike the eccentric fixation of 40 strabismic amblyopes studied by von Noorden and Mackensen,[15] our patients did not fixate retinally "nasal and slightly above" the foveola. Specifically, Patient 1 fixated retinally nasal-inferior to the foveolar position, Patient 2 temporal-superior, and Patient 3 temporal-inferior. None of the patients fixated in a way that placed the scotoma visually below the area fixated as observed by Aulhorn (cited by von Noorden and Mackensen[15]). Patients 1 and 3 fixated in a way that placed the scotoma(s) predominantly to the visual left of the object fixated,

whereas the scotoma surrounded the fixated area in Patient 2. In summary, there appears to be no simple rule for placement of the fixation locus with respect to the scotoma for our patients.

Each of our patients used only a single fixation locus (the one identified in Figs. 5–7). Throughout testing and in subsequent videotape review, we saw no indication that the patients ever used another retinal area to fixate. When asked to fixate targets turned on at random locations in the raster (but outside the patient's scotoma), the patients placed the target in the fixation locus, and did not first attempt to place it in the foveola. Thus, patients exhibited the "eccentric fixation" sequence described by von Noorden[16] for patients with longstanding bilateral macular scotomas. Indeed, our patients had documented macular scotomas for periods of 20–28 months, and two of them (1 and 3) used the tested eye exclusively since acuity in their other eye was 20/300 and 20/200, respectively. Patient 2, however, had 20/20 acuity in her normal contralateral eye. Why then did she develop a fixation locus in the eye with the macular scotoma? Even though clinically measured acuity in the scotomatous eye was 20/300, it has been found that, with acuities of this magnitude, it is still possible to have stereopsis.[17] One possible explanation, then, for Patient 2's fixational behavior is that she specifically tried to use her damaged eye (as she reported) to obtain "depth perception" in her work as a craftsperson. Thus, she may have used the small preserved area of vision within the scotoma to obtain stereopsis and hence developed a fixation locus.

Other laboratories also report a high incidence of a unitary fixation locus in patients with macular disease. For example, White and Bedell[18] found that 90% of their patients with aging macular degeneration or Stargardt's disease used a single retinal fixation locus. Those patients not having a single fixation locus had macular disorders for less than 24 months. Similarly, Cummings and Whittaker[19] reported that 70% of patiens with aging macular disease, Stargardt's disease, or macular holes used a single retinal fixation locus, although scotoma duration was not specified. The finding that some patients with macular scotomas do not use a single fixation locus[18,19] may differ from our findings due to differences in the fixation task, scotoma duration, type of macular disease, or patient sample size.

Fixation Stability

Patients' fixation with their eccentric fixation locus was less stable than normal, foveal fixation. Bivariate areas ranged from 507 to 623 min arc^2 (Table 1), approximately nine times those for foveal fixation by ocularly normal people.[20,21] It is to be expected that fixation stability will be poorer the more eccentric the fixation locus, but there are few data regarding the ability of ocularly normal subjects to fixate using extrafoveal retinal loci. Available information indicates, however, that the patients studied here fixate as stably or more so than ocular normals at approximately the same eccentricity. For example, Sansbury et al[20] found BVA's of 788 and 1,087 min arc^2 for subjects who fixated between two disks 10° apart (i.e., each target was 5° eccentric to the foveola). In comparison, Patient 1, whose fixation locus was 3.8° eccentric, had a BVA of 623 min arc^2, about 21% smaller than the smallest BVA found by Sansbury et al at 5°.

Bivariate areas for fixation eccentricities less than 5° are not available, but there are some measurements of horizontal standard deviations (SDs) of eye position for smaller eccentricities which can be compared with our data.[22] For 2° and 1° eccentricities, horizontal SDs were 7.5–14-min arc, and 4.5–13-min arc, respectively.[22] Patient 2 fixated 1.5° eccentrically with a horizontal SD of 9.0-min arc, within the normal range, whereas Patient 3 fixated 1.1° eccentrically with a SD of 7.4-min arc, slightly better than normal. In summary, the fixation stabilities of the patients we studied were poorer than normal foveal fixation, but as good as or better than the fixation stability of normal subjects trying to fixate eccentrically. This comparison must, however, be regarded cautiously since the fixation tasks for the normal subjects were not necessarily equivalent to the fixation task faced by our patients. In addition, our patients have "practiced" fixation with eccentric retinal loci for 20 months or more, and the normal subjects undoubtedly spent little more than a few hours. Thus, it may be possible to acquire more stable eccentric fixation with practice.

Fixation stability of our patients was also better than that reported for other patients with macular disease. For example, White and Bedell[18] found fixation stabilities of 18–82-min arc (average of horizontal and vertical SDs) for their patients with Stargardt's disease or aging macular disease. The largest horizontal SD found with our patients was 10.3-min arc. Whittaker et al[19,23] report fixation areas (roughly equivalent to BVAs) of from 1,000 to 12,000 min arc^2, much larger than the 507–623-min arc^2 found in the present study. Comparison of these data is difficult, however, since fixation tasks were different, measures of fixation stability were not exactly the same, and eccentricity was not specified in the other studies.

Fixation stability was not systematically related to fixation locus eccentricity, although the single largest BVA was found for the most eccentric fixation locus (Patient 1, Table 1). Patient 2, however, exhibited the lowest BVA of the three patients, but her fixation locus eccentricity was intermediate to the other two. This conclusion must be regarded with caution, however, because there is uncertainty as to the location of patient 2's foveola due to retinal distortion caused by scar for-

mation. Finally, it should be noted that, although von Noorden and Mackensen[15] found a general increase in fixation area (i.e., poorer fixation stability) with increasing fixation eccentricity for amblyopes, their data show many exceptions to the rule. Thus, the present data may reflect individual fixation stability differences such as those found in the normal population.[21]

The present results are consistent with von Noorden and Mackensen's observation that the size of the fixation area is not well correlated with visual acuity.[15] For example, Patient 2 had the smallest BVA (507-min arc^2) and also the poorest acuity (20/300). This is clinically relevant because it indicates that residual visual acuity cannot be predicted from fixation eccentricity by reference to standard acuity vs eccentricity curves. This could mean that the acuity of the fixation locus is abnormal for its particular retinal eccentricity or that the fixation locus is not used to inspect acuity targets in a clinical setting.

In conclusion, each of three patients with longstanding macular scotomas that we studied used a single, idiosyncratic retinal locus to fixate small targets. The fixation locus was immediately adjacent to the macular scotoma, but not necessarily as close as possible to the foveolar position. None of the patients had been explicitly trained to use a particular retinal locus inspecting visual detail, but each somehow "selected" a particular area. Why this location was selected is unclear, but the area may represent an optimal trade-off between visual quality (e.g., acuity), interference by the scotoma (e.g., obscuration of text), and proximity to the foveola, the retinal area previously associated with the visual "straight-ahead" position.

Key words: macular scotoma, scanning laser ophthalmoscope, fixation, reading, central visual field

Acknowledgments

The authors thank Drs. Robert Webb and George Hughes for invaluable technical help and Mr. Tom Monego for photographing the video display. Ms. Gail Collas and Mr. Anthony Morandi provided indispensable help in patient selection, scheduling, and performance of clinical tests.

References

1. Ferris FL: Senile macular degeneration: Review of epidemiologic features. Am J Epidemiol 118:132, 1983.
2. Brown B: Reading performance in low vision patients: Relation to contrast and contrast sensitivity. Am J Optom Physiol Opt 58:218, 1981.
3. Legge GE, Rubin GS, Pelli DG, and Schleske MM: Psychophysics of reading-II. Low vision. Vision Res 25:253, 1985.
4. Rayner K and Bertera JH: Reading without a fovea. Science 206:468, 1979.
5. Webb RH and Hughes GW: Scanning laser ophthalmoscope. IEEE Trans Biomed Eng 28:488, 1981.
6. Mainster MA, Timberlake GT, Webb RH, and Hughes GW: Scanning laser ophthalmoscopy—clinical applications. Ophthalmology 89:852, 1982.
7. Timberlake GT, Mainster MA, Webb RH, Hughes GW, and Trempe CL: Retinal localization of scotomata by scanning laser ophthalmoscopy. Invest Ophthalmol Vis Sci 22:91, 1982.
8. Webb RH, Hughes GW, and Pomerantzeff O: Flying spot TV ophthalmoscope. Appl Opt 19:2991, 1980.
9. Delori FC, Parker JS, and Mainster MA: Light levels in fundus photography and fluorescein angiography. Vision Res 20:1099, 1980.
10. Straatsma BR, Landers MB, Krieger AE, and Apt L: Topography of the adult human retina. *In* The Retina: Morphology, Function, and Clinical Characteristics, Straatsma BR, Hall MO, Allen RA, and Crescitelli F, editors. Berkeley, University of California Press, 1969, pp. 379–410.
11. Steinman RM: Effect of target size, luminance, and color on monocular fixation. J Opt Soc Am 55:1158, 1965.
12. Committee on Vision: Basic factors in visual field testing. *In* First Interprofessional Standard For Visual Field Testing. Washington, D.C., National Academy of Sciences, 1975, pp. 9–31.
13. Hart WM and Burde RM: Three-dimensional topography of the central visual field—sparing of foveal sensitivity in macular disease. Ophthalmology 90:1028, 1983.
14. Weiter JJ, Wing GL, Trempe CL, and Mainster MA: Visual acuity related to retinal distance from the fovea in macular disease. Ann Ophthalmol 16:174, 1984.
15. von Noorden GK and Mackensen G: Phenomenology of eccentric fixation. Am J Ophthalmol 53:642, 1962.
16. von Noorden GK: Atlas of Strabismus. St. Louis, C. V. Mosby, 1977, pp. 84–86.
17. Peli E: Normal stereo acuity despite anisometropic amblyopia. J Am Optom Assoc 54:919, 1983.
18. White JM and Bedell HE: Eye movements in patients with macular disease. ARVO Abstracts. Invest Ophthalmol Vis Sci 26(Suppl):259, 1985.
19. Cummings RW and Whittaker SG: Development of eccentric fixation following loss of macular vision. ARVO Abstracts. Invest Ophthalmol Vis Sci 26(Suppl):216, 1985.
20. Sansbury RV, Skavenski AA, Haddad GM, and Steinman RM: Normal fixation of eccentric targets. J Opt Soc Am 63:612, 1973.
21. Ditchburn RW: Eye Movements and Visual Perception. Oxford, Clarendon Press, 1973, pp. 97–98.
22. Bedell HE, Barbeito R, and Aitsebaomo PA: The precision of oculocentric direction and its role in the stability of fixation. Vision Res 24:1157, 1984.
23. Whittaker S, Cummings R, and Budd J: Fixation eye movements of people with macular scotoma. ARVO Abstracts. Invest Ophthalmol Vis Sci 25(Suppl):264, 1984.