Reading With a Macular Scotoma

II. Retinal Locus For Scanning Text

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To elucidate how patients with macular scotomas use residual functional retina for inspecting visual detail and reading, we tested three patients with dense macular scotomas using a scanning laser ophthalmoscope that allows an examiner to view and record stimuli on the retina while the patient views them. Using standard psychophysical techniques, we determined the retinal position of scotomas, the retinal areas used for fixating and inspecting acuity targets, and the retinal area used for reading simple, three-letter, nonsense syllables. We found that each patient used a single, idiosyncratic retinal area, immediately adjacent to the scotoma, for fixating, inspecting acuity targets, and scanning simple, nonsense-syllable text. This preferred retinal locus (PRL) was at different retinal eccentricities (relative to the foveola) for each patient and was not always as close as possible to the foveola. There appears to be no simple rule by which patients "select" a particular PRL. Plots of text placement on the retina revealed considerable differences in patients' abilities to execute an orderly text scan. Two patients read text more rapidly with a novel retinal area than with their PRL, suggesting that the PRL may not be optimal for text reading. Invest Ophthalmol Vis Sci 28:1268–1274, 1987

When individuals with normal vision read, saccadic eye movements shift the fovea along the retinal image of the text line, and the fixational oculomotor system (slow control and microsaccades) holds the fovea on text characters during fixations that last approximately 250 milliseconds.[1] During this time, approximately seven text characters are processed.[1,2] Subsequent saccades bring text that is farther along in the text line to the fovea, where it in turn is held for inspection and interpretation. This sequence of saccades and fixations is repeated millions of times by the experienced reader at rates that allow hundreds of words to be read each minute. Dense macular scotomas dramatically impair performance of this skilled visuomotor-cognitive task. When foveal function is eliminated permanently by a macular scotoma[3,4] or temporarily by artificial means,[2] the reading rate may be reduced to a few words per minute.

Many patients with macular scotomas learn to read with the aid of an optical or electronic magnifier, probably by placing the magnified text on a new, nonfoveal retinal area and scanning the text with this "pseudo-fovea." Even with such aids, however, reading rates of individuals with central visual loss are lower than the rates of those with other types of visual loss.[3] Knowing how patients with macular scotomas actually use residual functional retina to read is important for understanding and compensating for this severe reading loss. For example, what is the retinal location of the presumed pseudo-fovea? Is the pseudo-fovea optimal for reading in terms of its position with respect to the scotoma and its spatial visual capacity for text recognition?

In a previous report[5] we described the retinal locations of scotomas and the areas used by patients with macular disease to fixate. We found that each patient used a single, unique retinal area, immediately adjacent to the scotoma, for fixating. In the present study we used the scanning laser ophthalmoscope (SLO) to present acuity targets and simple text to the same patients to determine whether this fixation locus is also used for other visual tasks requiring the inspection of fine detail and for reading. We also investigated whether the text could be read with another retinal area besides the one habitually used by the patient.

Materials and Methods

Techniques for mapping the retinal location of the scotoma and the fixation area with the SLO have

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Presented in part at the annual meeting of the Association for Research in Vision and Ophthalmology, Sarasota, Florida, April 30–May 4, 1984.

Supported by NEI grant EY-03966 (GTT).

Submitted for publication: July 18, 1986.

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been described.[5] In the present experiments we also used computer-generated Snellen E acuity targets and simple text to map the retinal locations used for inspecting acuity targets and for reading.

Acuity Targets

Single, high-contrast Snellen E's with randomly chosen orientations were presented in the SLO raster. The patient identified the orientation of the E's (left, right, up, or down) by pressing one of four switches. Patients were encouraged to inspect acuity targets with whatever retinal area they wished to; the instruction was, "Look at the letters just as though you were having your acuity measured in the clinic." The computer controlled the stimulus size in 0.1 log unit steps (size factors of 1.26) in a staircase fashion: two correct responses resulted in a smaller target on the next trial; a single incorrect response, a larger target on the next trial.[6] Audible tones signalled the patient whether the judgment of E orientation was correct or incorrect. This procedure gradually reduced target size toward threshold acuity, although threshold was seldom reached because of SLO limitations (see *Discussion*).

Retinal positions of acuity targets were documented by computer measurement of digitized, videotaped SLO images made during testing.[5] We measured the retinal position of the target center, at least one-third of a second (ie, ten or more video frames) before the patient pressed the response switch. Approximately ten trials were measured for each patient, sampled during the time when targets were near threshold.

Text

To determine the retinal area used for reading, we used simple, meaningless, but easily pronounceable three-letter syllables[7] (eg, BAS, NAR, SEM). We chose such nonsense syllables so that patients' reading rates would not be affected by reading experience and knowledge of English words. Individual syllables were entered into the computer by manually digitizing printed Helvetica medium letters. Letter size in the SLO raster was adjustable in factors of two, resulting in letter stroke widths of 7, 14, 28, and 56 min arc. Overall letter size was approximately five times the stroke width (as in acuity letters), and the letters in a syllable were separated by the width of an average letter.

We asked the patients to "look at" the syllables in

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sented in random order, starting with the smallest size first. If the patient was unable to read three or more syllables, letter size was increased to the next

Fig. 1. SLO video image showing retinal location of the nonsense syllable CIG being read by Patient 1 when asked to read it any way she chose. (SLO images of retina shown here have been electronically rotated so that text and stimuli are oriented in the same way the patient views them: inferior retina at the top of each fundus image, nasal retina toward the optic disk.)

larger size until all 18 were read correctly. The patient's voice was recorded on videotape with the SLO fundus image showing the retinal locus of the syllable. Figure 1 is an example of the SLO image seen while the patient read one syllable.

Since many hundreds of video frames had to be analyzed to determine the retinal location of syllables during reading, we did not use the relatively slow computer measurement technique. Instead, we placed a clear acetate sheet over the screen of the video monitor displaying the SLO images of the patient's retina and traced the retinal blood vessels on the sheet. A grid was then drawn on the sheet, with each grid block having sides equal to the width of one letter plus one space. Thus, when the sheet was appropriately oriented on the SLO images, each letter of the syllable on the retina fit into one block of the grid, and three consecutive blocks were occupied by letters. The videotape was replayed one frame at a time, starting when the syllable first appeared and ending when the patient finished reading it. We shifted the acetate sheet on each stopped frame so that the vessels drawn on it lined up with those in the video image, and then marked each grid block that contained a letter. The next frame was then displayed

or more grid blocks, the experimenter assigned its position to the block that contained the greatest letter area.

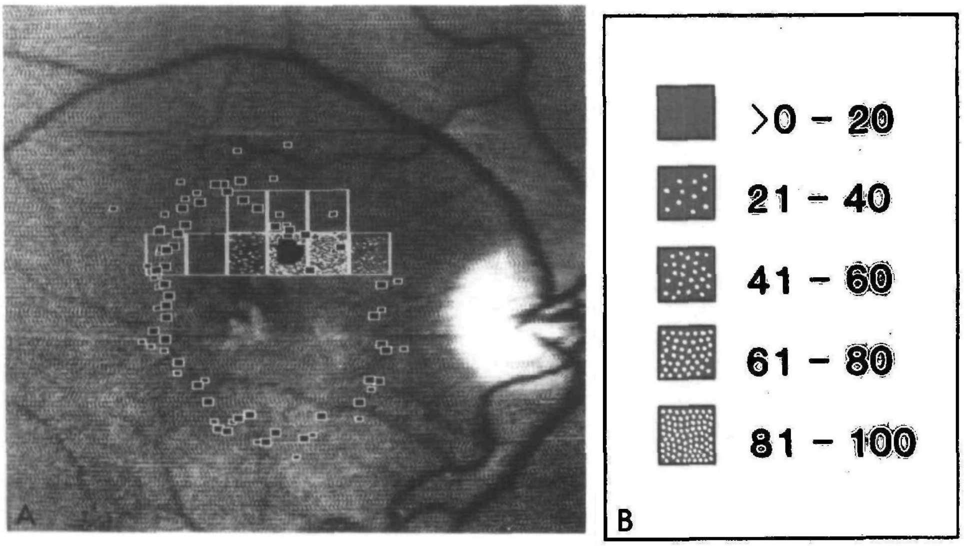

Fig. 2. (A) Patient 1. Retinal locus map showing retinal positions of scotoma, area used to fixate, and area on which letters were placed during reading. *Scotoma:* Small white/black squares outline scotoma border. Each white/black square shows retinal location at which mapping stimulus first became visible as it moved radially outward from center. Smaller squares, 14 × 14 min arc mapping stimulus; larger squares, 28 × 28 min arc stimulus. *Fixation area:* Retinal area used to fixate indicated by solid black squares that together form irregular, black area at scotoma border. (Fixation area appears to be within scotoma, but this is an artifact of the kinetic perimetric technique.) *Reading locus:* Large white squares with stippling show where syllable letters were placed on retina during reading. Syllable letters spent most time on the grid block containing the fixation and acuity area (100%). This is the PRL. The next most occupied grid block, to the right of the PRL, was occupied 91% of the time. Syllable letters were never placed outside grid shown. Reading rate, 1.5 letters/sec. **(B)** Stippling key in syllable reading plots. Density of stippling indicates percentage of time syllable letter occupied the grid block. Numbers at right show percentages of time a letter occupied the block.

From 20 to 300 video frames were analyzed for each syllable, depending on the patient's reading rate. The completed acetate sheet showed how many times a letter had been placed in each grid block. From this, we calculated the percentage of time a letter occupied each block, and the grid was then plotted on SLO retinal maps that also showed the retinal location of the scotoma, the fixation locus, and the areas used to inspect acuity targets. The percentage of time each block was occupied by a letter is indicated by stippling: the denser the stippling, the greater the percentage of time a letter was in the block (Fig. 2B).

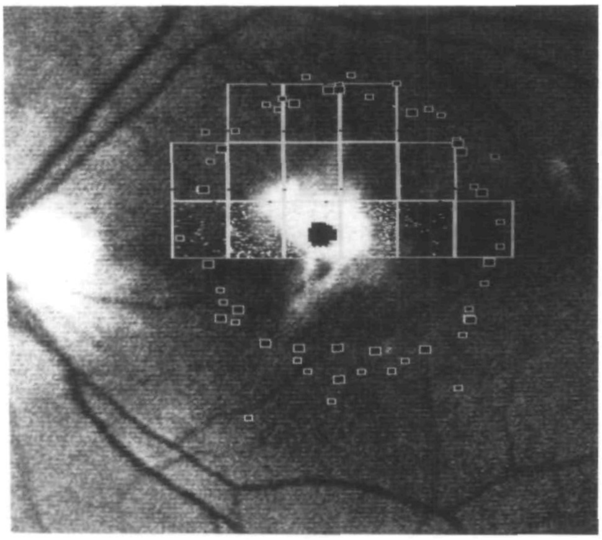

Fig. 3. Patient 2. Retinal locus map of left eye, with traumatic macular scar. Fixation area (irregular black rectangular area on scar) indicates region of preserved vision within large, circular scotoma (shown by white/black squares). Syllable letters spent most time on the grid block containing the fixation and acuity area (85.5%) (see stippling key in Fig. 2B). To the left of this PRL is the next most occupied block (62.9%). Reading rate, 0.3 letters/sec.

Patients

We tested the same three patients with dense macular scotomas for whom we previously mapped the retinal locations of scotomas and fixation areas.[5] Patient 1 had exudative macular degeneration; patient 2, a traumatic macular scar; and patient 3, atrophic macular degeneration. The purposes and procedures of the tests were explained to the patients, and signed, informed consent was obtained.

Results

Figures 2 to 4 show SLO retinal maps[5] of the scotoma, fixation area, and syllable placement during reading. The plots have been corrected for retinal shifts due to eye movements and thus show the true retinal locations of the stimuli.[5]

Fixation and Acuity Target Areas

Within the limits of our ability to specify stimulus position, all three patients used a single retinal area for fixation and for inspecting acuity targets.

For clarity in Figures 2–4, the acuity target area has not been plotted. Detailed plots of both acuity- and fixation-target retinal positions are shown in Figure 5 for Patients 2 and 3. For both patients, acuity targets *appear* to have been inspected with a retinal area slightly displaced (note scale) from the fixation area. These retinal loci, however, represent the centers of the fixation and Snellen E targets, which are drawn to scale in Figure 5B. We have no assurance that the patients actually looked at target center, however, and they may have instead chosen to inspect some other aspect of the target such as an edge. For example, had we measured the retinal locations of the right edge of the fixation stimulus, fixation and acuity areas in Figure 5A would overlap completely. Thus, although the two targets appear to be separated horizontally in Figure 5, the separation is less than the overall size of the fixation target and most likely came about because the patients inspected some aspect of the targets other than the center.

We could not plot fixation- and acuity-target locations on the same plot for Patient 1 because we presented the acuity targets with a smaller (higher-resolution) SLO raster, and our computer analysis program could not compensate for a size difference this large. Separate plots of the two stimuli are shown in Figure 6. Both fixation and acuity targets were placed on the same small whitish area of retina at the apparent terminus of a blood vessel that travels from the upper right to the lower left (inferotemporally).

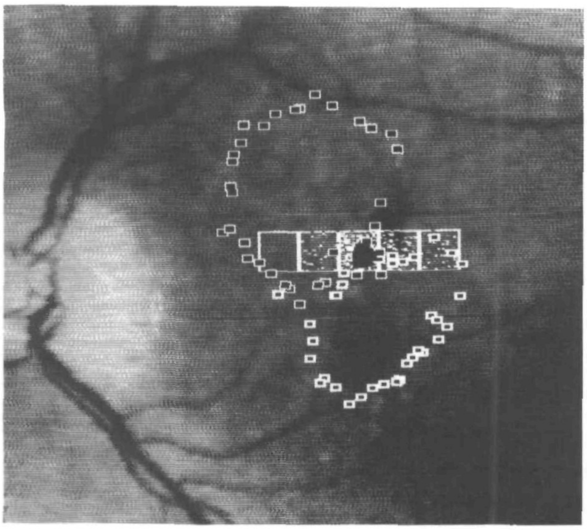

Fig. 4. Patient 3. Retinal locus map of right eye of 73-year-old woman with atrophic macular degeneration shows two contiguous scotomas (mapping stimulus size, 28 min arc). Fixation area (irregular, black area) is within small gap formed by the two scotomas. Syllable letters spent most time on the grid block containing the fixation and acuity area (100%) (see stippling key in Fig. 2B) The PRL was placed on syllable letters in an orderly sequence (cf. Figs. 2 and 3). Next most frequently occupied grid block was to the left of the PRL (75.5%). Reading rate, 1.2 letters/sec.

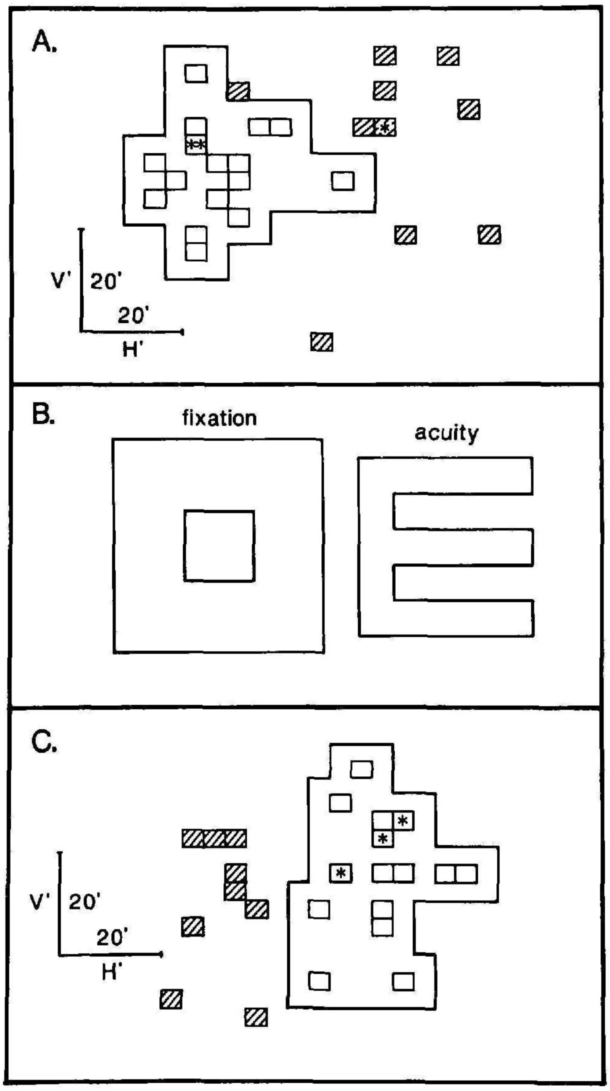

Fig. 5. Graphic plots showing detail of fixation and acuity target retinal placements. (**A**) Patient 2. Empty squares show placements of fixation target center; they are enclosed by a line showing outline of area plotted in Figure 3. Cross-hatched squares show relative retinal position of acuity target centers. Asterisks indicate multiple placements. Note highly expanded scale of these plots as shown by calibration marks at lower left. (**B**) Scale drawings of fixation stimulus and smallest acuity stimulus. Centers of these targets on the retina were measured to produce the plots in (**A**) and (**C**) and in Figures 3 and 4. (**C**) Patient 3.

Retinal Locus For Reading Syllables

Retinal placement of syllables during reading is indicated by the stippled blocks in Figures 2–4. Letters were not placed on retinal areas shown without grid blocks. For all three patients, syllable letters spent the greatest time in the block that encloses the area used for fixating and for inspecting acuity targets, indicating that this retinal area was also used to read the syllables. Thus, each patient used a preferred retinal

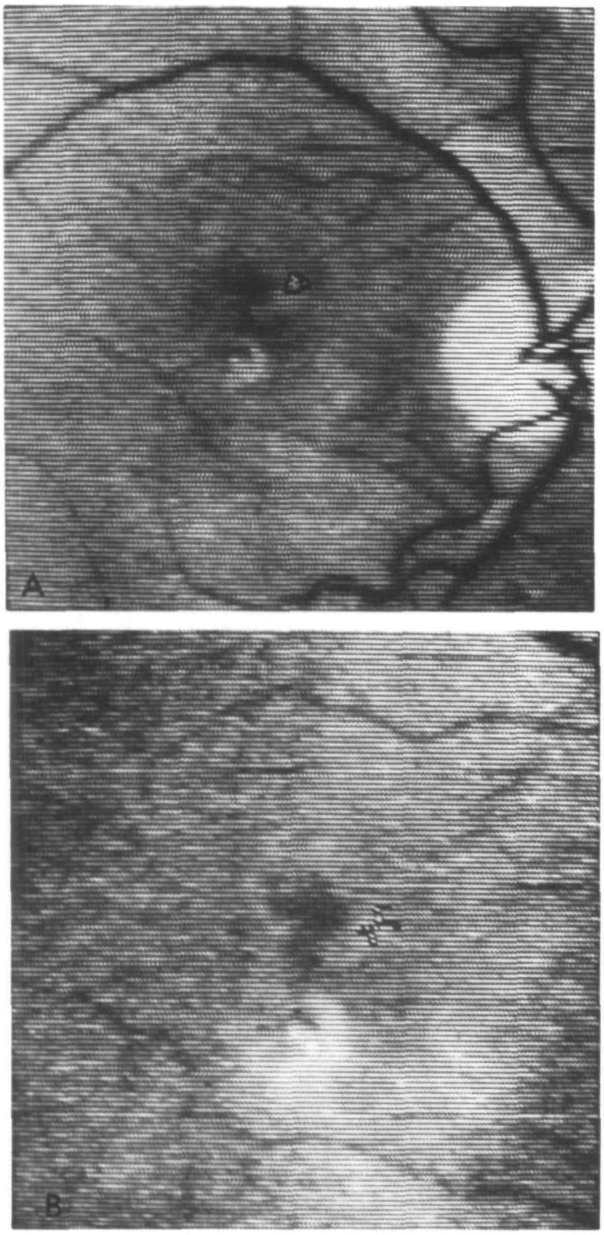

Fig. 6. Patient 1. (A) SLO retinal plot showing location of fixation-target placements (dark area with white dots) as shown in Figure 2, but without scotoma or reading plot. (B) Retinal locus used for inspecting acuity stimuli shown by dark squares with white dots. This SLO image was recorded at higher magnification than (A). Note that acuity stimuli, like fixation stimuli shown in (A), were placed on whitish area to right of darkly pigmented area.

locus (PRL), immediately adjacent to the scotoma, for fixating, inspecting acuity targets, and scanning text.

Syllable Scanning by the PRL

If the PRL did not scan the syllable (ie, move from letter to letter) but fixed only one letter and held that position while the syllable was read, the reading plot would show three side-by-side blocks with identical stippling. Alternatively, if the PRL were never placed on the letters, there would be no grid block surrounding it. Finally, if the PRL fixated each letter in turn for equal amounts of time, the plot would show five side-by-side blocks with the center block most frequently occupied by a letter. Patient 3 exhibited just this type of distribution (Fig. 4), indicating a very orderly text scan. Often, however, letters were within scotomatous retinal regions to the left of the PRL and just grazed the scotoma to the right (Fig. 4). Patient 3 read at the rate of 1.2 letters/sec, or about 14 words per minute (wpm) (assuming an average of five letters/word in ordinary text).

Patients 1 and 2 were less successful in executing the orderly scanning sequence. Patient 1 occasionally looked below the syllable with her PRL (row of grid blocks above PRL) (Fig. 2) and sometimes to the right of the entire syllable (grid block at left-hand scotoma boundary). Nevertheless, patient 1 had the fastest reading rate of the three patients, 1.5 letters/sec (18 wpm).

Patient 2 attempted to scan syllables with the small preserved area of vision within the large, circular scotoma (Fig. 3). Probably only one letter at a time was visible in the small PRL, and letters to the left or right, within the scotoma, were not seen. When Patient 2 attempted to shift the PRL saccadically to an adjacent unseen letter, the saccade was often too large, and the entire syllable became located in the scotoma. Patient 2 adopted the strategy of looking downward, then upward, bringing the letters back into the PRL. This complicated sequence of retinal shifts placed syllables briefly in the top portion of the scotoma (Fig. 3). Syllable letters were, nevertheless, placed most frequently on the PRL, but the reading rate was quite low, 0.3 letters/sec (about 4 wpm).

Reading With an Alternate Retinal Locus

After the patients read the syllables with a retinal area of their own choosing (the PRL), we asked them to try to read with a different retinal area. Specifically, we asked Patients 1 and 2 to "put your blind spot (scotoma) above (or below) the syllables and try to read them." The syllables were presented again, in different order, and the patient read them aloud. Retinal areas used for this "eccentric" reading are shown in Figure 7. Both patients confined the syllables to a relatively well-localized retinal area that was above and to the right (Patient 1) or below and to the left (Patient 2) of the scotoma. Reading rates were faster with the novel retinal locus than with the PRL. Patient 1 read 1.8 letters/sec (22 wpm) with the novel locus and 1.5 letters/sec (18 wpm) with the PRL, a modest increase. Patient 2 tripled her reading rate with the novel retinal locus, 0.9 letters/sec (11 wpm) rather than 0.3 letters/sec (4 wpm).

Discussion

Over 20 years ago, von Noorden and Mackensen[8] discovered that patients with a longstanding macular scotoma used an eccentric retinal locus for fixating, but until recently little additional information was available. The work presented here and in our previous report[5] indicates that the retinal area discovered by von Noorden and Mackensen is used not only to fixate, but also to inspect acuity targets and read simple text. This retinal area acts like a pseudo-fovea, taking over from the nonfunctional fovea the task of inspecting visual detail. We have coined the neutral term preferred retinal locus (PRL) for this area, habitually used by patients with macular scotomas for inspecting visual detail. This finding may be useful to the clinician in terms of treatment or low-vision rehabilitation since it means that the retinal area a patient uses for reading can be identified by finding the area used for fixation as, for example, by fixation fundus photography.

Each of the three patients we studied had a *single* PRL, and a review of videotaped SLO images for other patients also indicate the use of a single PRL. Cummings et al[9] reported that 72% of their patients with macular scotomas used a single locus for inspecting threshold acuity targets, but a few used multiple loci. This difference in findings is most likely the result of the instructions given the patient and the methods of data analysis. We instructed patients to press a switch when they felt they were looking at the fixation target, and we analyzed retinal stimulus position only when the switch was pressed. Cummings et al[9] asked patients to look at a threshold acuity target for 12 sec and analyzed the entire trial including, in principle, periods when fixation was "lost." This might result in the spurious identification of multiple PRLs. Nevertheless, we have tested only three patients, and it is conceivable that some patients will be found who use different retinal areas for inspecting different targets.

The PRL is immediately adjacent to the scotoma but at different eccentricities relative to the foveola for each patient.[5] There appears to be no systematic rule for PRL placement; it can be below, to the side, or even within the scotoma (with central preservation) for different patients. Furthermore, the PRL is not always as close as possible to the foveolar position.[5] The PRL might be "selected" because: (1) its position results in the least obscuration by the scotoma of text to-be-read; (2) it is in the retinal region of highest visual acuity; or (3) a trade-off between these two factors. Although we can identify instances in which PRL location seems to result in minimal obscuration by the scotoma of text to-be-read (see Figs. 2A, 4), we were unable to determine whether the PRL was the retinal location of highest residual acuity. The primary reason for the inability to measure acuity was that our Generation-I SLO had limited graphics resolution in the laser beam raster, with each pixel 7 min arc wide. Thus, the smallest acuity-target gap

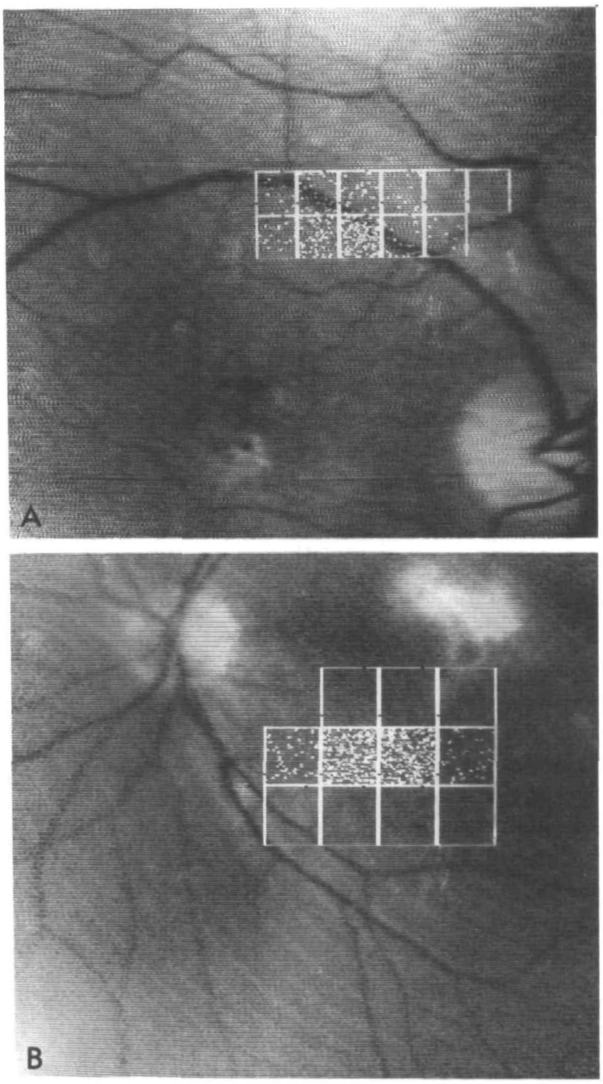

Fig. 7. Retinal reading locus plot summarizing syllable placement when patient was asked to "put your blind spot (scotoma) below the syllable and read it." (A) Patient 1. Retinal area occupied by syllable letters was larger than when reading with the PRL (cf. Fig. 2). Note that this "eccentric" reading area is just above and to the right of the scotoma. Reading rate, 1.8 letters/sec. (B) Patient 2. Syllables were most frequently placed just at the lower left edge of the scotoma (cf. Fig. 3). Reading rate was three times greater than with the PRL (0.9 letters/sec).

was 7 min arc, or 20/140. In addition, the small entrance pupil (1 mm diameter in the patient's pupil), the relatively high light levels, and the very high target contrast produced by turning the laser beam off all tend to maximize visual acuity.[10] Thus, acuities with the SLO are better than those measured clinically.

Acuity measurements are now possible with our recently completed Generation-II SLO that has much higher target resolution than did the original instrument.[11]

Our finding that reading rates improved (albeit modestly) when patients were asked to read with a retinal area other than their PRL suggests that the PRL may not be optimal for reading. This is undoubtedly true for Patient 2 who used a small preserved area within a large scotoma to attempt reading. Mandelbaum and Sloan[12] also encountered similar cases and reported improved reading when the patients were instructed to read with an area outside the scotoma. The SLO is particularly valuable in this instance since one can readily identify small preserved areas that occur relatively often[13] but are undetected by standard perimetry, and monitor text position on the retina in order to instruct the patient where to place the text. Patient 1's modest increase in reading rate could be a result of practice since she viewed the 18 nonsense syllables first with the PRL and then with the alternate reading area. Memorization seems unlikely, however, because of the number and random order of the syllables. Furthermore, it is conceivable that nonsense syllables are read differently than normal extended text. We will explore this possibility by using simple extended sentences.

Finally, recent research by Legge et al[3] indicates that reading deficits caused by central visual loss (scotomas) are different from, and more severe than, those caused by other common visual impairments such as ocular media abnormalities and peripheral field loss. These investigators suggest that the especially poor reading ability of those with macular disease might result from poor control of eye movement, or even that central retina may have unique capacities for reading. Understanding and alleviating the particularly severe reading difficulties of those with macular scotomas described by Legge would benefit, we believe, by knowing where text is actually placed on the retina, whether the scotoma obscures some text, and whether the text is on the retinal area of highest residual acuity. We will explore these problems with the second-generation SLO.

Key words: macular scotoma, scanning laser ophthalmoscope, visual acuity, reading, retinal image, eccentric viewing

Acknowledgments

The authors thank Mr. Tom Monego for photographing the video display, Mr. Anthony Morandi for conducting clinical psychophysical tests, and the Retina Associates for making their resources available to us. Finally, we thank the subjects in this study for their time, interest, and patience.

References

1. Morrison RE: Retinal image size and the perceptual span in reading. *In* Eye Movements in Reading: Perceptual and Language Processes, Rayner K, editor. New York, Academic Press, 1983, pp. 31–40.
2. Rayner K and Bertera JH: Reading without a fovea. Science 206:468, 1979.
3. Legge GE, Rubin GS, Pelli DG, and Schleske MM: Psychophysics of reading. II: Low vision. Vision Res 25:253, 1985.
4. Brown B: Reading performance in low vision patients: Relation to contrast and contrast sensitivity. Am J Optom Physiol Opt 58:218, 1981.
5. Timberlake GT, Mainster MA, Peli E, Augliere RA, Essock EA, and Arend LE: Reading with a macular scotoma. I: Retinal location of scotoma and fixation area. Invest Ophthalmol Vis Sci 27:1137, 1986.
6. Timberlake GT, Mainster MA, and Schepens CL: Automated clinical visual acuity testing. Am J Ophthalmol 90:369, 1980.
7. Hilgard ER: Methods and procedures in the study of learning. *In* Handbook of Experimental Psychology, Stevens SS, editor. New York, John Wiley, 1951, pp. 539–592.
8. von Noorden GK and Mackensen G: Phenomenology of eccentric fixation. Am J Ophthalmol 53:642, 1962.
9. Cummings RW, Whittaker SG, Watson GR, and Budd JM: Scanning characters and reading with a central scotoma. Am J Optom Physiol Opt 62:833, 1985.
10. Riggs LA: Visual acuity. *In* Vision and Visual Perception, Graham CH, editor. New York, John Wiley, 1965, pp. 334–339.
11. Timberlake GT, Augliere R, Peli E, Webb R, and Hughes G: Generation-II clinical scanning laser ophthalmoscope. ARVO Abstracts. Invest Ophthalmol Vis Sci 27(Suppl):313, 1986.
12. Mandelbaum J and Sloan LP: Peripheral visual acuity with special reference to scotopic illumination. Am J Ophthalmol 30:581, 1947.
13. Hart WM Jr and Burde RM: Three-dimensional topography of the central visual field: Sparing of foveal sensitivity in macular disease. Ophthalmology 90:1028, 1983.