Grating, Vernier, and Letter Acuity in Retinitis Pigmentosa

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Grating, vernier, and letter acuities were compared in 25 patients with retinitis pigmentosa (RP), whose Snellen visual acuities were better than 20/40, to address the mechanism of visual acuity loss. For these patients with RP, all three types of visual acuity were reduced to an equivalent degree from those of a control group of 10 age-similar, visually normal subjects. The findings indicate that the visual acuity losses of these subjects with RP did not result from cone spatial undersampling (due, for example, to a random loss of foveal cones), from cone sampling irregularities (due to random alterations in foveal cone position), or from a selective loss of sensitivity to high spatial frequencies (as might result from changes in media transmission characteristics or a gain reduction in high spatial frequency mechanisms). In addition, previous studies have indicated that acuity losses in such patients with RP do not result from reductions in the quantum-catching ability of foveal cones. The most likely explanation for the equivalent losses in all three acuity types in these patients with RP appears to be an alteration in foveal spatial scale, consistent with a generalized increase in foveal intercone spacing. Invest Ophthalmol Vis Sci 33:3400–3406, 1992

Patients with retinitis pigmentosa (RP) frequently have reductions in foveal visual acuity in addition to peripheral visual field defects.1,2 The exact explanation for the foveal acuity losses of patients with RP is not entirely clear. One possibility is that the acuity loss results from a reduction in the quantum-catching ability of the foveal cones.3 This hypothesis is consistent with a reduced foveal cone optical density that has been inferred from the abnormal Rayleigh matches of patients with RP,4,5 as well as with histologic evidence of cone outer segment abnormalities in RP donor eyes.6 However, recent studies indicate that this is not the major explanation for acuity reductions of patients with RP who have visual acuities of 20/40 or better.7–9 For example, subjects with RP within this acuity range do not show the improved visual acuity at high light levels that would be expected if a reduced quantal catch were the primary reason for their acuity loss.8

An alternative explanation for the acuity loss of patients with RP is a decrease in the spatial density of foveal cones (ie, the number of cones per unit area of retina).7–9 This possibility is consistent with the results of a histologic study of the donor eye of a patient with RP who had reportedly normal visual acuity. The study demonstrated evidence of a reduced spatial density of foveolar cones with no alterations in foveal cone outer segment morphology.10

A decrease in cone spatial density might occur in several ways, each with different consequences for the sampling properties of the foveal cone photoreceptor array.11 One possibility (A) is that there is spatial undersampling by foveal cones, because of a loss of sampling units. In patients with RP, alternative A would occur, for example, if there were a random loss of cone photoreceptors from the foveolar array. A second possibility (B) is sampling irregularity resulting from random changes in the position of the sampling units. In patients with RP, alternative B could occur if there were an increased variability in the position of foveolar cones. This would most likely occur with alternative A because position irregularity is unlikely to occur in the presence of a normal complement of foveolar cones. A third possibility (C) is a uniform change in the spatial scale of the fovea. In patients with RP, alternative C would occur if there were a general increase in the center-to-center spacing of the foveolar cone photoreceptors (without actual foveal photoreceptor loss).

Previous studies have indicated that these alternative explanations for visual acuity loss can be tested.
through a comparison of vernier, grating, and letter acuities. Alternative A (spatial undersampling) should have little effect on grating or vernier acuity, as discussed by Wilson. Alternative B (sampling irregularity) would reduce vernier acuity to a greater extent than grating acuity, as has been shown in patients with strabismic amblyopia, and in the normal parafovea. Evidence suggests that alternative B also should reduce letter acuity more than grating acuity. Alternative C (uniform change in retinal spatial scale) would reduce all three types of acuity equivalently because proportionately larger-than-normal stimulus dimensions would be required to perform the acuity tasks. The present study investigated these alternative explanations for the visual acuity loss of subjects with RP by comparing reductions in these three types of visual acuity.

Subjects and Methods

Subjects

Twenty-five patients (9 women and 16 men) with typical RP or Usher's syndrome and a mean age of 36.6 yr (standard deviation 10.0 yr) participated in the study. Based on criteria established previously, four subjects had autosomal-dominant RP (all were type 2 according to the classification of Massof and Finkelstein), one had autosomal-recessive RP, 14 were isolated cases of RP (no other family member was known to be affected), three had RP of uncertain genetic type, and three had type 2 Usher's syndrome (a recessively inherited variant of RP accompanied by a congenital neurosensory hearing impairment). All patients with RP or Usher's syndrome had best-corrected pretest Snellen visual acuities ranging from 20/15 to 20/30, minimal or no lens opacities, no atrophic-appearing foveal lesions, and no macular cysts, although seven had mild epiretinal macular membranes.

Results were compared with those from 10 (six women and four men) age-similar (mean age ± SD 32.4 ± 10.1 yr) subjects with normal vision. All normal subjects had best-corrected Snellen visual acuities of at least 20/20, clear ocular media, and normal-appearing fundi by ophthalmologic examination. Informed consent was obtained from all subjects after the nature of the testing procedures had been explained fully.

Test Stimuli

The acuity targets were presented on an Apple high-resolution gray-scale display monitor controlled by a Macintosh II computer (Apple Computer, Cupertino, CA). Test targets were viewed monocularly through a 2 mm artificial pupil, with an appropriate refractive correction in a phorometer. The target duration was 270 msec, with a brief warning tone preceding each target presentation. The interstimulus interval typically was 2–3 sec, during which time the subject's response was entered into the computer by the examiner and the next stimulus was generated. Target contrast (C) was defined by Weber's relationship:

\[ C = \frac{L_T - L_B}{L_B} \]

where \( L_T \) refers to target luminance and \( L_B \) to background luminance. For all conditions, \( L_T = 0 \) and \( L_B = 2.5 \) log td, as calibrated with a Spectra Spotmeter (Kollmorgen, Newburgh, NY), so that \( C = -1.0 \).

Three types of acuity targets were used, as illustrated in Figure 1. Grating acuity was measured with a pattern of five black bars (Fig. 1A). Bar length was varied randomly from trial to trial by ±1% relative to pattern width to avoid extraneous cues to the orientation of the grating pattern. Vernier acuity was measured with a chevron pattern (Fig. 1B). This stimulus configuration was chosen so the distinction between the fixed stimulus and variable stimulus could be conveyed easily to the subjects. The angle of the chevron was 62°, and there was no gap between the chevron and horizontal bar. Vernier target size was chosen such that patients with RP who had a Snellen visual acuity of 20/40 could resolve the chevron. Letter acuity was measured with isolated Sloan letters (Fig. 1C). Targets were viewed in a front surface mirror at a distance of 7.2 m (grating and letter acuities) or 13.2 m (vernier acuity).

Procedure

Each test condition was preceded by a brief practice session in which the procedure was explained and representative stimuli were displayed. For each subject, the test conditions were presented in order of vernier, letter, and grating acuity. These test conditions were repeated in counterbalanced order, and the results from the two repetitions were averaged.

Vernier acuity was measured with an adaptive staircase procedure that was a modified version of the method proposed by Fendick. On each trial, subjects were asked to respond whether the horizontal bar appeared to be above or below the tip of the chevron (no "equal" responses were allowed). Two staircases with mirror-symmetric decision rules were run concurrently. One staircase employed a two-down, one-up decision rule, such that two "above" responses were required before the bar was displaced downward, while one "below" response resulted in an upward displacement of the bar. The second staircase

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Fig. 1. Stimulus configurations for grating (A), vernier (B), and letter (C) acuity measurements.

... employed a two-up, one-down rule, in which two "below" responses were required for an upward displacement of the bar, while one "above" response was followed by a downward displacement.

For both vernier staircases, the step size was 1 pixel, which corresponded to 5 arcsec. The staircases ended when eight reversals had occurred in each. The reversal points in each staircase were averaged. The resulting two mean displacement values provided estimates of the 29% and 71% points on a psychometric function relating percentage "above" responses to vertical displacement of the bar. These two mean displacement values then were used to obtain vernier bias and vernier threshold, two separate components of vernier acuity. Vernier bias (or accuracy) refers to the point of subjective alignment between the vernier targets. Bias was defined as the midpoint between the two mean reversal points. Vernier threshold refers to the just-detectable offset of the vernier targets from the point of subjective alignment. Vernier threshold was defined as one-half the magnitude of the total displacement between the two mean reversal points.

Letter acuity was measured according to the modified Bailey-Lovie procedure, as adapted for the present testing apparatus. Isolated Sloan letters were presented sequentially in sets of five at each of a series of log MAR (minimum angle of resolution) values. Testing was begun at a log MAR value of 20/100, and subjects were asked to identify each of the five letters within a set. After each set, letter size was decreased by 0.1 log MAR. Testing was continued until the subject failed to report correctly any of the five letters within a set. Each letter read correctly was assigned a value of 0.02 log MAR, and letter acuity was defined as the total log MAR score.

Grating acuity was measured with a two-alternative forced-choice staircase, with a step size of 0.1 log MAR. The bars of the grating were horizontal or vertical on each trial, with the orientation determined by a Fellows sequence. Subjects were instructed to identify the bar orientation on each trial. The staircase ended when eight reversals had occurred. A two-down, one-up decision rule was used to provide an estimate of the 71% correct point on a psychometric function relating percentage correct to grating log MAR.

Control Experiment

A control experiment was performed on four additional visually normal subjects (mean age ± SD 30.8 ± 9.6 yr) to confirm that the stimulus configurations for grating and vernier acuity were appropriate for assessing mechanisms of acuity loss. Two variations of the standard test protocol were introduced, with conditions chosen to produce approximately a two-fold reduction in grating acuity compared to the standard foveal viewing condition. First, the vernier and grating targets were presented at 4° in the nasal visual field of the normal subjects, with fixation guided by a dim long-wavelength light-emitting diode. Previous studies have shown that presenting the test targets at such a parafoveal test locus produces a greater reduction in grating acuity compared to the standard foveal viewing condition. First, the vernier and grating targets were presented at 4° in the nasal visual field of the normal subjects, with fixation guided by a dim long-wavelength light-emitting diode. Previous studies have shown that presenting the test targets at such a parafoveal test locus produces a greater reduction in vernier than of grating acuity, presumably due mostly to changes in the spatial sampling characteristics of the parafoveal retina. However, other properties of the parafoveal cone photoreceptors, such as reductions in quantum catching ability, also may play...
Second, the vernier and grating targets were viewed through a ground glass diffuser placed at an appropriate distance in front of the display monitor. Diffusive blur, which reduces the high spatial frequency content of the visual stimuli, has been shown to cause a greater reduction of grating than of vernier acuity.

Results

Figure 2 presents the results of the control experiment designed to confirm the appropriateness of the grating and vernier stimulus configurations for assessing mechanisms of acuity loss. The filled circle in this figure represents the baseline condition, in which the acuity targets were presented to the optically corrected foveas of four visually normal subjects. Equivalent changes in vernier threshold and grating acuity away from this baseline condition are represented by the diagonal line with unit slope. The presentation of the test targets at 4° in the nasal visual field (filled square; Fig. 2) resulted in a greater change in vernier threshold than in grating acuity, to a degree that is consistent with results reported previously.

As a result, these stimulus conditions were affected in appropriate ways by sampling irregularity (parafoveal test locus) and loss of high spatial frequencies (diffusive blur). The relationship between log grating acuity and log vernier threshold for the 25 patients with RP and 10 normal subjects is presented in Figure 3. The normal subjects had a mean grating acuity of 0.87 arcmin (approximately 20/17 Snellen equivalent) and a mean vernier threshold of 12.2 arcsec, with approximately equal variance in both measures. There was a statistically significant correlation of 0.73 (t(23) = 5.12, P < 0.01) between grating acuity and vernier thresholds for the patients with RP. Four patients with RP had grating acuities and vernier thresholds that fell within the 95% confidence limits for the normal values, as defined by a Gaussian bivariate ellipsoid. The remainder of the patients with RP had grating acuities that were reduced and vernier thresholds that were elevated by approximately equivalent amounts from the normal values. This relationship is illustrated by the fact that the acuity values of these patients with RP were within the limits defined by the shaded region in Figure 3.
cal alignment of the chevron tip and horizontal bar ($t_9 = -0.45, P$ is not significant). Five patients with RP had vernier threshold and bias values that fell within the 95% confidence limits for the normal subjects (Gaussian bivariate ellipsoid; Fig. 4). The majority (17) of the other patients with RP had bias values within the variability of normal, as defined by this ellipsoid (shaded region; Fig. 4). Only three patients with RP had bias values beyond the normal limits. The data from these three patients with RP also lay outside the normal range if the bias values are considered as percentages of the threshold values.

The patients with RP had equivalent reductions in grating and letter acuities, as illustrated in Figure 5. The mean grating and letter acuities of the normal subjects were 0.87 arcmin (approximately 20/17) and 0.77 arcmin (approximately 20/15), respectively. For the patients with RP, there was a statistically significant correlation of 0.93 ($t_{23} = 11.95, P < 0.01$) between these two acuity measures, as well as a statistically significant multiple correlation of 0.95 among letter, grating, and vernier acuities ($F_{2,22} = 94.41, P < 0.01$). Four patients with RP had values of grating and letter acuity within the Gaussian bivariate ellipsoid that defined the 95% confidence limits for the normal subjects. The other 21 patients with RP had equivalent reductions in both grating and letter acuity, indicated by the fact that their acuity values fell within, or in one case just beyond, the shaded region in Figure 5.

**Discussion**

In this group of 25 patients with RP, letter acuity was reduced and vernier thresholds were elevated in direct proportion to reductions in grating acuity. The equivalent change in all three types of visual acuity indicates that the acuity losses exhibited by the subjects with RP were not due to spatial undersampling resulting from loss of cone photoreceptors (alternative A) or to sampling irregularity resulting from random alterations in cone position (alternative B). As already described, a marked loss of foveal cone photoreceptors would have little effect on grating or vernier acuity,11 while sampling irregularity would produce a greater deficit in vernier acuity than in grating acuity.11,12

Moreover, our results also argue against another class of explanations for visual acuity losses in these patients with RP, specifically that there is a selective loss of sensitivity to high spatial frequencies.29 Such a selective sensitivity loss could occur in patients with RP if there were changes in the ocular media equivalent to diffusive blur, or, alternatively, if there were a selective gain reduction in high-spatial-frequency mechanisms. As illustrated in Figure 2, a selective sensitivity loss at high spatial frequencies would reduce grating acuity more than vernier acuity, because vernier acuity is relatively more resistant to the loss of high spatial frequencies.27,28 Contrary to this expectation, the loss of vernier acuity was equivalent to that for grating acuity in this group of patients with RP.
Our results are most consistent with alternative C, that the foveas of these patients with RP are spatially scaled versions of the normal fovea, such that proportionally greater-than-normal stimulus dimensions are required by the patients with RP to perform these three types of acuity tasks. A possible mechanism for such a change in foveal spatial scaling is a more-or-less uniform increase in intercone spacing, perhaps resulting from a generalized enlargement of foveal cones secondary to degeneration of parafoveal rod and cone photoreceptors. Consistent with this hypothesis is a recent histologic study that showed an enlargement of foveal cone inner and outer segments in the fovea of donor eyes obtained from a patient with autosomal dominantly inherited RP and reportedly normal Snellen acuity. In addition, it has been proposed that abnormalities in the Stiles-Crawford effect found in patients with RP with mild acuity losses were more consistent with morphologic abnormalities in the width and shape of foveal cone photoreceptors than with increased foveal cone disarray, shortened cone outer segments, or reduced numbers of foveal cones.

The majority (22/25) of our patients with RP had vernier bias values within normal limits, despite elevations in their vernier thresholds. Consequently, these patients were able to identify correctly the point at which the vernier targets were aligned, although they required a greater displacement than normal to detect misalignment of the targets. Similarly, Turano reported that in a bisection task involving parafoveal and foveal target presentation, most patients with RP had normal bias values. The explanation for the abnormal vernier bias values for three of the patients with RP in our study is uncertain. However, the abnormal biases may represent a mild degree of metamorphopsia in their foveas, perhaps resulting from distortions in the foveal cone photoreceptor lattice.

In conclusion, gratings, vernier, and letter acuities were reduced equivalently in this group of patients with RP whose Snellen acuities were better than 20/40. These results indicate that neither spatial undersampling resulting from loss of cone photoreceptors, sampling irregularity, nor a selective sensitivity loss at high spatial frequencies can account for their loss of visual acuity. Instead, the findings are most consistent with a change in the spatial scale of the foveas of these patients with RP. The most likely explanation for such a change in spatial scaling appears to be a relatively uniform increase in foveolar cone spacing, perhaps due to a generalized enlargement of foveal cone inner segments. Although such a mechanism may account for mild degrees of visual acuity loss in patients with RP, it remains to be determined whether other factors contribute to acuity reductions in those patients with RP whose Snellen acuities are worse than 20/40.

Key words: cones, resolution, retinitis pigmentosa, vernier, visual acuity

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