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The Temporal Visuogram in Ocular Hypertension and its Progression to Glaucoma

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Summary: In a study of progression to glaucoma in ocular hypertensive eyes followed for at least 4 years, temporal flicker sensitivity measured at the beginning of the period was evaluated as a predictor of the likelihood of progression. Significantly abnormal temporal visuograms at a 1% criterion predicted progression in 9 of 10 eyes that developed glaucomatous losses. Temporal visuograms for locations in the nasal arcuate area (15° nasal to fixation) showed much greater sensitivity to visual loss than those in the central part of the retina. Comparison with threshold perimetry losses showed that patients within the normal range on the central four points were also within normal range on the temporal visuogram. Peripheral flicker testing was more sensitive than threshold perimetry to losses in the nasal arcuate area in glaucoma patients. **Key Words:** Temporal visuogram—Ocular hypertension.

Sensitivity to sinusoidal temporal modulation (flicker sensitivity) for a uniform stimulus field has recently been applied to ophthalmological diagnosis. Flicker sensitivity has been shown to provide earlier detection in glaucoma patients than with previously available tests (1,2), to measure a reversible component of the visual susceptibility to disease (3), to provide differential diagnosis among conditions that cannot be differentiated by other tests (4), to characterize the nature of the sensory deficit (4,5), and to provide information as to which retinal mechanisms are affected by the disease (4–6).

In previous work we have used flicker sensitivity to evaluate the temporal losses in patients with glaucoma, ocular hypertension, and other optic neuropathies. If a test is to make an improvement in diagnosis, it should be able to predict functional losses due to the disease earlier than current tests. The temporal visuogram of flicker sensitivity losses provides a sensitive measure of visual loss in glaucoma (1,7). It has not been shown whether flicker sensitivity loss is predictive of a subsequent glaucomatous field loss in ocular hypertensive (OH) eyes, although Casson and Johnson (2) have described flicker sensitivity losses preceding progression from ocular hypertension to glaucoma in a few patients. Our study was designed to test the hypothesis that flicker testing can predict subsequent glaucomatous field loss.

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METHODS

Temporal Visuogram

The methods for measuring the temporal visuograms were similar to those in previous studies (8,9). Briefly, amplitude thresholds were measured for flicker frequencies in half-octave steps from 2.5 Hz upward, in addition to the critical fusion frequency (CFF). The sinusoidal flicker was presented in a half-second raised-cosine envelope in a stimulus consisting of a red, 660-nm LED array that was diffused to appear as a uniform red disk and set in

an equiluminant white surround of 400 cd/m^2. This stimulus wavelength specification has been developed to optimize the assessment of retinal function and minimize contamination from optical factors. It uses long wavelength light to isolate cone responses and, together with the equiluminant white surround, to eliminate any rod contribution to detectability (10,11). The long-wavelength test stimulus also minimizes contamination from refractive distortions, aging of the lens, and early media opacities (12,13). The fact that it is narrowband light also minimizes chromatic aberrations.

The 660-nm test disk was viewed at 27.5 cm so as to have an angular subtense of 5°. It was viewed centrally in study A and either centrally or at 15° in the upper or lower nasal field in study B. This stimulus configuration has been developed for assessment of photopic vision across a range of retinal and optic nerve disorders (1,3–9). In addition to the advantages described above, the use of a large test stimulus minimizes the effects of defocus on the temporal visuogram (8) and enhances the visual sensitivity to flicker at high frequencies, where glaucomatous losses predominate.

Psychophysical Staircase Procedure

The test procedure consisted of a Yes/No task for flicker detection with 20% blank trials as a check on the false-alarm response rate. The overall paradigm consisted of a cyclic interleaved staircase procedure, in which the staircases for all stimulus frequencies were interleaved in cyclic rotation. For the fixed frequency staircases, stimulus amplitude (modulation depth) was decreased by one step (viz., 0.1 log units) for a Yes response, but increased by three steps for a No response. (Thus a perfectly accurate No should represent threshold, and should be followed by three Yes responses as the staircase jumped up and tracked down to threshold again). The staircase was terminated when a No response was obtained on the same or adjacent modulation levels as the preceding No response. The threshold was considered to be the average flicker amplitude at these two criterion No responses.

The CFF was first measured alone by means of a similar descending staircase procedure. For the CFF measurements only, the staircase had a variable step size. The sequence began at 5 Hz and increased in 5-Hz steps of frequency until the first No response was obtained. The subsequent staircase operated by 1-Hz frequency steps, on the same three-up/one-down paradigm as for modulation amplitude, until two subsequent No responses were obtained at the same or adjacent frequency steps. The resulting CFF value was used to set the subsequent range of frequencies used for the second phase of the test, the measurement of modulation sensitivity at fixed frequencies.

Having selected the applicable frequency range, the algorithm then cycled through the chosen test frequencies in sequence, obtaining one response for each frequency before changing to the next. Each response then was used to determine the value presented at that frequency the next time around, following the same algorithm as for CFF except that each step was 1 decilog (27%) of modulation amplitude. The staircase for each frequency proceeded independently (although temporally intermixed) until two subsequent No responses were obtained on the same or adjacent flicker levels.

The data were screened for reliability on the basis of the false-positive response rate in the 20% blank trials included as an indication of the observers' attention to the task and response criterion. This feature resulted in the presentation of an average of 8 ± 3 blank trials during a typical test run. The observers were allowed no more than two false-positive responses for an acceptable performance. Pupil size was measured and the observer was excluded if the pupil diameter lay outside the limits of 2.5–3.5 mm.

Each eye was tested separately, with the untested eye occluded by an opaque patch. In study A, one eye from each patient was selected at random for testing, except for the unilateral glaucoma group, in which the glaucomatous eye was always tested. In study B, only the right eye was tested. A typical test run for one eye would take ~10 min for 10 frequencies, because the run lengths varied between ~40 and 100 or more trials, according to when the criteria were met. The optimal values for the termination criteria were ascertained by computer simulation of hundreds of runs; measured psychophysical thresholds had close to the simulated variability even in untrained observers.

The temporal visuogram was scored as showing a significant loss at the 1% criterion on the distribution of normal sensitivities (99% specificity level) if a single value fell more than 2.3 SDs below the normal mean value at any test frequency, or if two or more adjacent frequencies both fell >1.6 SDs below normal (which also meets the 1% criterion for the number of points being tested). The 1% significance

level is generally regarded as providing sufficient protection against multiple applications of the test. In the application to study A, this protection level would have resulted in 20% of the "significant" losses observed being attributable to chance alone, which is unlikely to have produced a substantial distortion of the reported results. This is an acceptable false-positive rate in view of the fact that the patients could be retested to reduce that rate to a negligible level if the test were being applied in clinical practice.

PREDICTING PROGRESSION TO GLAUCOMATOUS FIELD LOSS

The study consisted of two parts—the relation of flicker sensitivity losses to losses recorded on Goldmann kinetic perimetry, and the evaluation of the predictive value of the visuogram test in OH eyes for the onset of Goldmann field loss. A series of patients attending a glaucoma clinic was tested with the temporal visuogram and the loss obtained at the frequency of 28 Hz compared with the severity of deficit on kinetic perimetry. Another series of patients with OH eyes, defined as those with elevated intraocular pressure (IOP) but no significant loss on kinetic perimetry, was followed for up to 8 years (average 5 years), depending on their initial enrollment in the study and the duration over which they continued to attend the clinic. The criterion for elevated IOP was a pressure of >21 mm Hg on any previous ophthalmological examination.

The patient sample was drawn from the population of the Glaucoma Clinic at California Pacific Medical Center. To evaluate the relation of Goldmann field losses to visuogram losses at 28 Hz, we used a population with a wide range of field defects. In addition to the 52 normal volunteers ranging in age from 15 to 75 years, the 72 patients were categorized into the following groups: (a) bilateral OH (OH > 21 mm Hg on any examination, Goldmann field < 1.8, see later here in) (b) unilateral glaucoma (Goldmann field > 2.0), and (c) bilateral glaucoma (Goldmann field > 2.0). One eye from each patient was selected for analysis at random from each of the groups, except for the unilateral glaucoma group, in which the glaucomatous eye was always used. The age range of this full group of patients was 23–92 years, with a mean of 64 years. The ability of the temporal visuogram to show a loss that would predict the onset of glaucomatous field losses was in OH patients evaluated for an initial enrollment of 48 patients.

The Goldmann fields for all eyes were evaluated independently in a masked procedure by two clinicians experienced in Goldmann field analysis, without knowledge of the patient's history or other ocular conditions. The mean value of the two assessments was used to specify the severity of loss for quantitative analysis. A scale of severity was developed to define a numerical value for the glaucomatous loss evident in the Goldmann fields, as follows: 0—Normal; 1.0—Slight nonspecific abnormalities (slightly enlarged blind-spot, slight concentric contraction); 1.5—Definite but nonspecific abnormalities (moderately enlarged blind-spot, generalized contraction); 2.0—Probable glaucomatous loss (probable Bjerrum scotoma; asymmetric contraction); 2.5—Mild but definite glaucomatous loss (definite Bjerrum scotoma to I2e, small nasal step > 5°); 3.0—Moderate glaucomatous loss (arcuate scotoma, nasal step approaching fixation, two-quadrant loss); 3.5—Advanced glaucomatous loss (defect crossing fixation, altitudinal defect, more than two-quadrant loss); and 4.0—Extreme glaucomatous loss (field reduced to <10°).

The main aim of the study was to look at the ability of the visuogram test to predict the progression to glaucomatous visual field loss in OH eyes. For this study, OH was defined as elevated IOP in an eye with Goldmann field loss of <2.0. This criterion included anything that could be regarded as a normal field or one with nonspecific losses that might be attributable to the normal aging process. Fields were measured on a yearly basis and the complete history of each patient's fields was used in the assessment of progression to glaucoma. No patient was regarded as having progressed unless all fields subsequent to the first one to reach the abnormal criterion also were abnormal. Both assessing clinicians had to agree that the field history showed a clinically significant progression before a patient was considered to have progressed. To be sure that progression had occurred, a field loss was not regarded as a significant glaucomatous loss until it reached a severity of 2.5 (mild but definite glaucomatous loss). Thus, progression was defined conservatively as a change from <2.0 to a score of ≥2.5, a change of at least 0.5 on the defined scale. The more severe deficit had to be maintained during subsequent tests to be considered reliable.

Forty-eight patients with at least one OH eye were initially tested. Of these, 13 discontinued their

attendance at the Glaucoma Clinic, 3 had invalid initial visuogram test results, and 6 died before the completion of the study. This left a total of 26 OH patients with progression information during 4 or more years, up to a maximum of 8 years. Their age range was 35–87 years with a mean of 58 years.

For this evaluation it was appropriate to include any OH eye in the sample, whether it came from a patient with bilateral OH (defined as low-risk eyes) or from a patient with unilateral glaucoma with ocular hypertension in the fellow eye (defined as a high-risk eye, because it is highly likely for the glaucoma to become bilateral at some time in the future). It was particularly important to include the high-risk eyes to obtain sufficient numbers of conversions to allow a statistical evaluation, because the conversion rate is known to be as low as 2% per year in bilateral OH.

RESULTS

A correlation analysis was performed on the 72 patient eyes, together with the data of one eye selected at random from each of the normal observers. The correlation derived from the Goldmann field score and the observer's loss relative to normal at a frequency of 28 Hz, which has been shown to be the most susceptible frequency in glaucoma (1). The Pearson correlation coefficient obtained was 0.477, which is statistically significant at $p < 0.01$. There is thus a clear but imperfect relationship between the Goldmann field loss and the flicker sensitivity loss, as has been found in previous studies (1,7).

In fact, of the 8 unilateral eyes we were able to follow for 5 years, 63% did progress to glaucomatous Goldmann field loss, as contrasted with 27% of the 18 bilateral OH patients. These high rates of progression may reflect patient preselection at a tertiary glaucoma center. A total of 10 eyes progressed to glaucoma (5 within 1 year of the visuogram test, the remainder scattered during the 5-year period). The predictive sensitivity of the test is shown in Table 1. Nine of the 10 patients who progressed had shown significant losses on the temporal visuogram by the criteria defined in Methods. This shows the test to have a predictive sensitivity of 90% at the specificity level of 99% for a population of age-matched normals; that is, 90% ocular hypertensives having a level of flicker loss seen in 1% of points tested based on previous comparable studies of large samples from the normal population (8,14) progressed to glaucomatous field loss within 5 years.

TABLE 1. *Predictive accuracy of temporal visuogram*

	Goldmann visual field	
Temporal visuogram	Progression	No progression
Loss	9	11
No loss	1	5

The right column of Table 1 shows that the predictive specificity for this population of ocular hypertensives was 31%. This low specificity value is attributable to the fact that the period for potential progression is open ended rather than being limited to the testing period, as elaborated in the Discussion. It therefore is more appropriate to use the specificity rate for flicker sensitivity in the normal population (8,14) for statistical analysis. There were an average of 15 applications of the statistical test for each of 26 patients, for a total of 390 applications. We therefore should expect a false-positive rate of ~4 significant results at the 1% level by chance alone, compared with the 20 that we found, implying a specificity of 80%. If used as the expected value in a χ^2 statistic for the cases of progression only (left column), the 90% sensitivity ratio in Table 1 is significant at $p < 0.01$.

COMPARISON OF THE SENSITIVITIES OF THE HUMPHREY FIELD ANALYZER AND THE TEMPORAL VISUOGRAM IN GLAUCOMA

The Humphrey visual field analyzer has become one of the most widely used diagnostic instruments for detection of glaucomatous visual deficits. This experiment compared the severity of nasal-step visual field losses for ocular hypertensives and glaucoma patients by automated perimetry and by temporal visuogram. Such losses by perimetry in the region 12–15° nasal to fixation, or the nasal arcuate region, represent nerve fiber layer loss in the papillomacular bundle. Upper/lower asymmetry in these losses is commonly considered a typical sign of glaucomatous damage (15,16). Temporal contrast sensitivity also has been reported to be reduced in the periphery in glaucoma (1,17,18). The study consisted of measuring flicker sensitivities at 15° superonasal and inferonasal to fixation in normals, ocular hypertensives, and glaucoma patients. Automated threshold perimetry using the Humphrey central 30-2 or central 24-2 protocols were administered to the ocular hypertensives and glaucoma patients.

TABLE 2. *Automated perimetry losses*

Group	N	MD dB ± SEM	Central dB	Upper dB	Lower dB
OH	6	−1.0 ± 0.4	−1.3 ± 0.8	−0.4 ± 0.7	−0.8 ± 0.3
Glaucoma	5	−6.6 ± 1.2	−6.0 ± 1.6	−7.3 ± 2.0	−9.8 ± 0.9
Difference		5.6	4.7	6.9	9.0

MD, mean deviation; OH, ocular hypertensive.

The patient sample was drawn from the same source as discussed in Predicting Progression to Glaucomatous Field Loss. For the purposes of this analysis, the right eye of each patient or normal volunteer was tested. Patients with a CFF <40 Hz on central flicker testing were excluded, as were subjects unable to perform reliably Humphrey perimetry with a size III test object. These criteria excluded de facto patients with severe glaucomatous defects involving fixation.

In addition to 24 normal volunteers, the 11 patients were categorized into two groups: ocular hypertensives with normal automated fields and glaucoma patients with significant losses on automated perimetry. The five patients in the ocular hypertensive group had a mean age of 59 years, and the six glaucoma patients had a mean age of 65 years.

Automated threshold perimetry (Humphrey Central 30-2 or Central 24-2) for all eyes was evaluated for average loss in sensitivity for all points tested in the upper and lower nasal arcuate area, i.e., 15–21° from fixation. OH patients had normal visual fields, with no significant mean deviation (MD) loss, and glaucoma patients had significant losses on visual fields (MD significant at $p < .01$). The average losses in the upper and lower arcuate areas for these two groups are summarized in Table 2, with an average MD of −1.0 dB (± 0.4 SEM) for ocular hypertensives and −6.6 dB (± 1.6) for glaucoma patients. The average loss in the four central points (comprising the central 3°) was −1.3 dB (± 0.8) for ocular hypertensives and −6.0 dB (±1.6) for glaucoma patients. The average loss in the upper nasal arcuate area was −0.4 dB (±0.7) for ocular hypertensives and −7.3 dB (± 2.0) for glaucoma patients. The average loss in the lower nasal arcuate area was −0.8 dB (±0.3) and −9.8 dB (±0.9) for glaucoma patients. The two groups of patients had differences of 5.6 dB in average MD, 4.7 dB in central loss, 6.9 dB in upper arcuate loss, and 9.0 dB in lower arcuate loss. Thus, by automated threshold perimetry, the losses in the lower nasal arcuate area were greater than MD losses for the central 24° or for the central 3°.

Fixation for the temporal visuogram was either central, 15° superotemporal, or 15° inferotemporal to the test disc, to test the superonasal and inferonasal arcuate areas, respectively.

RESULTS

CFFs for all regions tested are presented in Table 3. CFFs for ocular hypertensives and glaucoma patients were within the 95% confidence interval for normals (± 1.96 SEM).

Results for one glaucoma patient are presented in Fig. 1. The central region showed high frequency losses peaking around 30 Hz (open triangles, dashed line). The peripheral test regions showed dramatic losses peaking at lower frequencies, with sensitivities recovering almost to normal at the highest frequencies tested (40–45 Hz). The lower field was substantially more affected than the upper.

Mean central flicker sensitivity losses relative to normal for ocular hypertensives and glaucoma patients are presented in Fig. 2. Standard errors for each patient group were calculated at each frequency to allow discrimination of frequency-specific losses. Error bars represent 1 SEM. No central losses were seen at the lower frequencies for glaucoma patients or at any frequency for bilateral ocular hypertensives, in contrast to previous findings when glaucoma was defined by Goldmann field losses (1). This may be due to a difference in sensitivity to mild losses between the Humphrey and Goldmann perimeters. The fact that the group re-

TABLE 3. *Critical fusion frequencies for central and 15° peripheral areas*

Group	N	Central (Hz ± SEM)	Upper (Hz ± SEM)	Lower (Hz ± SEM)
Normal central	52	56.0 ± 0.5		
Normal peripheral	24		63.6 ± 3.8	68.7 ± 3.3
OH	6	55.0 ± 2.8	60.1 ± 2.3	64.1 ± 4.6
Glaucoma	5	52.0 ± 3.4	58.0 ± 4.1	61.0 ± 4.5

OH, ocular hypertensive.

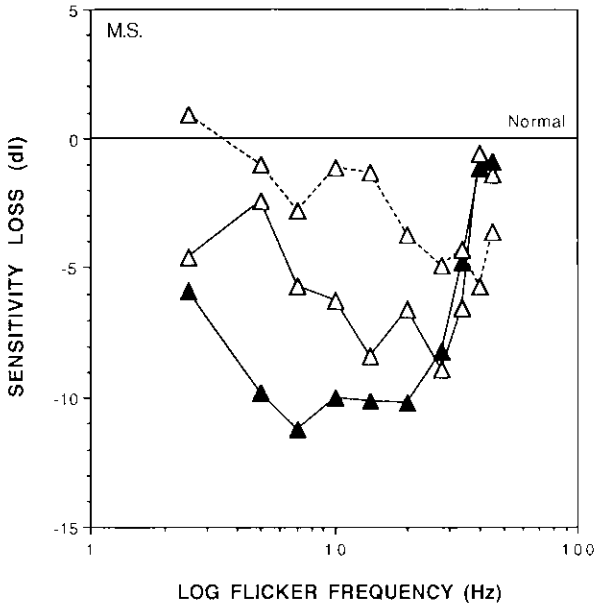

FIG. 1. Example of flicker sensitivity loss (in decilogs relative to normal) in a glaucoma patient. Flicker sensitivity losses for the central 5° (open triangles, dashed line) and for the upper (open triangles) and lower (filled triangles) nasal arcuate regions are plotted as a function of log flicker frequency. The central curve shows losses peaking around 30 Hz. Peripheral sensitivity losses are greater than central losses at all frequencies < 30 Hz. Peripheral sensitivity losses are greatest in the midfrequency range and approach normal at the highest frequencies.

sults for bilateral OH patients show no average losses cannot be compared directly with the 27% individual rate for significant losses in such patients seen in the section on Predicting Progression to Glaucomatous Field Loss. Because of the small numbers involved, it is not appropriate to attempt a similar analysis in the present study.

Peripheral flicker sensitivity losses from normal are presented in Fig. 3. The normal mean sensitivities for the upper (Fig. 3a) and lower (Fig. 3b) nasal field locations are shown in the upper panels. Ocular hypertensives showed normal sensitivity at all frequencies (circles in Fig. 3). Glaucoma patients, on the other hand, showed significant (> 1.96 SEM) losses at most frequencies tested, with greatest losses in a broad midfrequency range of 10–30 Hz (triangles in Fig. 3). The lower nasal arcuate field losses were greater than the upper nasal arcuate field losses for most of the range of frequencies tested, except for frequencies > 30 Hz.

Although glaucoma patients showed greater losses on peripheral flicker than on central flicker, it was noted that all patients had asymmetric visual field deficits by automated perimetry, i.e., either the upper or lower field showed consistently more loss. For a closer analysis of this visual field asymmetry on the temporal visuogram, we resorted the data to compare flicker sensitivity between better and worse arcuate fields. Each patient's data were evaluated in relation to the normal for the corresponding retinal location. Both mean sensitivity plots and losses in sensitivity for better and worse fields are presented in Fig. 4 for the group of glaucoma patients. The differences in flicker loss are greatest for the frequency range of 5–34 Hz, whereas CFF showed essentially no difference.

Comparison of peripheral flicker sensitivity losses in glaucoma patients (Fig. 3) to automated perimetry arcuate field losses (Table 2) shows that temporal losses at 2.5 Hz are approximately equal to the perimetric losses (0.3 decilog loss = 6 dB for the upper field, 0.45 dl = 9 dB for the lower field on the visuogram). Mean losses for frequencies over the range of 7–28 Hz are greater on the visuogram (10 dB in the upper field, 14 dB in the lower field for the visuogram) than on automated threshold perimetry, suggesting that peripheral flicker testing is more sensitive glaucomatous damage than automated threshold perimetry.

If the automated field losses for glaucoma patients are grouped according to better and worse fields, losses are 6.3 dB for the better field and 10.8

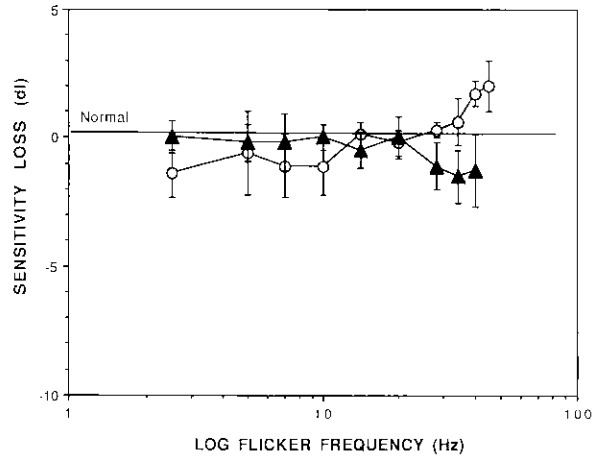

FIG. 2. Central flicker sensitivity loss in ocular hypertension and glaucoma. Flicker sensitivity losses (in decilogs relative to normal) for ocular hypertensives (open circles) and glaucoma patients (filled triangles) are plotted as a function of log flicker frequency from 2.5 to 45 Hz. Error bars represent 1 SEM. The only statistically significant difference ($p < 0.05$) between the two groups of patients, in which error bars do not overlap, is in the range of 30–45 Hz.

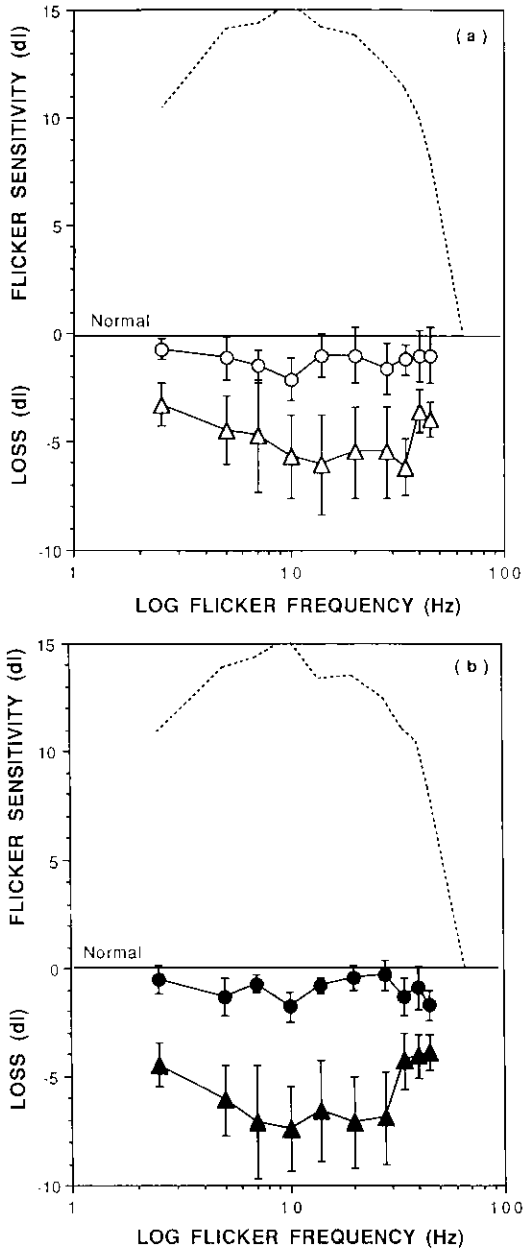

FIG. 3 Peripheral flicker sensitivity in normals (dashed lines) and loss (in decilogs) in ocular hypertension and glaucoma. Peripheral flicker sensitivity losses for upper (open symbols) **(A)** and lower (filled symbols) **(B)** nasal arcuate areas are plotted for ocular hypertensives (circles) and glaucoma patients (triangles). Error bars represent 1 SEM. Ocular hypertensives showed no significant losses at any frequency. Glaucoma patients showed significant losses at most frequencies tested in both upper and lower fields. Their losses were greatest over the range of 10–28 Hz and differed the most from ocular hypertensive losses for that same range.

dB for the worse field, compared with losses of 8dB (better) and 15 dB (worse) on temporal perimetry (Fig. 4). This again suggests a gain in sensitivity of ~50% with temporal flicker testing.

DISCUSSION

The experiment on predicting progression to glaucomatous loss provides strong statistical support for the previous suggestion (2) that temporal sensitivity losses can predict glaucomatous progression, when evaluated in relation to the specificity of the test in a normal population. Ideally it would be preferable to have a test that gives a normal response if the patient will not progress to glaucoma, but this is a difficult outcome to evaluate, because the eye could always progress after the end of any evaluation period less than the lifespan of the patients. For example, a progression rate of 27% every 5 years in the bilateral OH patients would give a total progression of 71% in 20 years. In this context, it should not be too surprising to see from Table 1 that the predictive specificity is only 31%, meaning that a loss was obtained on the visuogram for 69% of the eyes that had not progressed, because a similar proportion of these patients might be expected to progress in the future.

The experiment on comparison of sensitivities of the Humphrey Field Analyzer and the temporal

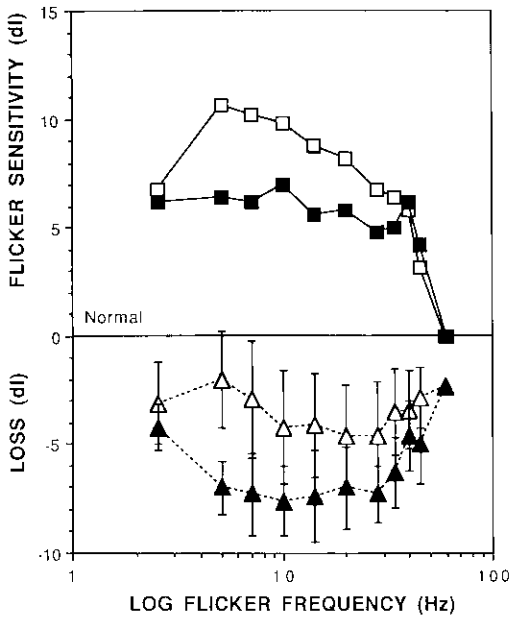

FIG. 4. Nasal-step comparison by peripheral flicker sensitivity in glaucoma. Peripheral flicker sensitivity (in decilogs) for better (open squares) and worse (filled squares) nasal arcuate fields in glaucoma patients is plotted in the upper panel. Losses (in decilogs relative to normal) for better (open triangles) and worse (filled triangles) fields are plotted in the lower panel. Error bars represent 1 SEM. The difference in losses between better and worse fields is greater at all frequencies (except critical fusion frequency) than between upper and lower field losses seen in Fig. 3.

visuogram confirms previous suggestions (1,17) that peripheral flicker losses are greater than those detected with central flicker testing. Comparison of automated perimetry and temporal flicker perimetry suggest that flicker losses for glaucoma patients in the nasal arcuate area are greater than those seen with automated perimetry. The midfrequency range of 10–30 Hz appears to be most sensitive in detecting deviations from normal. Flicker sensitivity was not reduced in ocular hypertensives, in contrast to previous reports in which peripheral losses for ocular hypertensives predominated around 40 Hz (1,19). This difference may reflect improved management of the IOP with current monitoring procedures compared with that of 15 years ago. Alternatively, it may be due to greater sensitivity of automated perimetry such that eyes previously classified as ocular hypertensive would now be termed glaucomatous.

The data suggest that a testing protocol employing 10–30-Hz peripheral flicker may be more sensitive in detecting and following early glaucomatous deficits than static perimetry or high-frequency flicker perimetry.

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