Contrast Sensitivity of the Human Pattern Electroretinogram

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Contrast thresholds for the pattern electroretinogram (PERG) were measured using lock-in amplifier retrieval of the retinal signal and a swept contrast display. Contrast sensitivity functions (CSF) developed from these PERG contrast thresholds were compared with those established psychophysically under identical stimulus conditions. Whereas the PERG CSF showed a band-pass characteristic across temporal frequency, the psychophysical CSF (and a temporal CSF developed from visual evoked potential contrast thresholds) had a low-pass pattern. Across spatial frequency, the PERG and psychophysical CSFs had similar shapes, although the PERG CSF peaked at a lower spatial frequency than the psychophysical CSF. Invest Ophthalmol Vis Sci 28:151–157, 1987.

It has recently been discovered that the electroretinogram (ERG) elicited with pattern reversal stimulation (the so-called pattern ERG, or PERG) is absent or reduced following section of the optic nerve in the cat1–3 or monkey,4,5 and in optic nerve disease in the human,6–9 while ERGs elicited by luminance increments remain normal. This suggests a dissociation between the two responses. Moreover, Maffei et al1–4 report a similar time course between decreased PERG amplitude and histologically revealed ganglion cell degeneration after optic nerve section. They conclude that the PERG reflects ganglion cell function. A response developed from this layer of the retina would allow investigation of a stage of the visual pathway that was previously unavailable by noninvasive methods.

To date, most research on the PERG has measured amplitude changes across spatial or temporal frequency using stimuli with contrasts well above threshold.10–19 Relatively little work has been focused on the threshold behavior of the PERG.20,21 In the present investigation, we have employed a swept stimulus technique22 to estimate PERG contrast thresholds across both temporal and spatial frequency. Knowledge of the PERG contrast sensitivity function (CSF) could allow comparisons with single cell work, and would also be of use in determining the degree to which the psychophysical CSF is retinally determined.

Materials and Methods

The apparatus consisted of a visual stimulator and an electrophysiological recording system. These are presented schematically in Figure 1, and are discussed in detail below.

Visual Stimulator

One-dimensional sine-wave gratings were displayed on a 16° by 22° video monitor (Conrac Model QQA 14 N/A, Coivre, CA) at a viewing distance of 71 cm. The monitor had a mean luminance of 33 cd/m² (Photo Research Spectra Spot Meter PR-1500, Burbank, CA). Background luminance was approximately 12 cd/m². A small spot in the center of the screen provided a point for fixation. An external control voltage, applied to the pattern generator (Institute of London), allowed percent contrast to be increased continuously (swept) from 0.1–20% over a 20-sec trial period while mean luminance remained constant. Percent contrast was defined as 

\[ \frac{(L_{\text{max}} - L_{\text{min}})}{(L_{\text{max}} + L_{\text{min}})} \times 100 \]

where \( L_{\text{max}} \) and \( L_{\text{min}} \) equal the brightest and dimmest levels, respectively, of the stimulus. The course of the sweep was approximately logarithmic. Spatial frequency and temporal alternation rate (square-wave contrast reversal) were each set by changing an external control voltage to the pattern generator.

Electrophysiological Recording System

Retinal signals were recorded from the right eye using a gold foil electrode inserted in the lower eyelid and
referenced to the right ear. This electrode is as reliable as the scleral lens electrode often used in ERG research. The left ear was grounded. To avoid recording an additional “crosstalk” PERG, the left eye was patched. The signal was amplified (Grass Model P511J AC preamplifier, Quincy, MA, gain = 10k, 1–100 Hz) and then fed into a pair of quadrature lock-in amplifiers (EG&G/PAR Ortec/Brookdeal 9505-SC, Princeton, NJ, time constant = 3 sec). These instruments multiplied (synchronously demodulated) the output with a sinusoidal reference signal at the reversal rate (i.e., at twice the frequency in Hz) and then integrated the product. Thus, the lock-in amplifiers retrieved only the second harmonic response component. The output was synchronously demodulated at four phase relations (phase sensitive detection) to the stimulus alternation (0°, 45°, 90°, 135°). Electrically inverted, this allowed eight logical phase relations around the clock in 45° steps.

The output of each lock-in amplifier channel was stored in a separate channel of a signal averager (Nicolet 1170B). The channel containing the signal was identified by separately calculating the response phase (θ = 1/tan (B/A)), where A and B represent the orthogonal (quadrature) outputs of one lock-in amplifier. A detailed description of these methods can be found in Nelson et al.

For purposes of comparison, the visual evoked potential (VEP) was also recorded. The active electrode was placed approximately 2 cm above the inion and referenced to the right ear. The left ear was grounded. The recording system was otherwise identical to that used to record the PERG.

### Procedure

**Electrophysiological trials:** A specific spatiotemporal condition was selected for each trial. Seated in a comfortable chair, the subject fixated the center of the screen and signalled when ready. Stimulus contrast was then swept, from 0.1–20% over the 20-sec trial period. To avoid possible adaptation effects in the PERG or VEP, contrast was swept upward. This was repeated four to six times. When a set of trials was accumulated for a given condition, the next spatiotemporal stimulus was set and a new series of trials began.

A temporal CSF was determined for the PERG and for the VEP using a 1.0 cycle/degree (cpd) sine-wave grating. A spatial CSF was determined for the PERG using sine-wave gratings presented at a reversal rate of 5 alternations/second (alt/sec).

**Psychophysical trials:** For each stimulus condition, monocular psychophysical contrast thresholds were separately obtained. To facilitate comparison with electrophysiological trials, an ascending method of limits was used. The subject increased the contrast of the stimulus to threshold using a potentiometer. The criterion for visibility was any detectable change from a uniform field. All parameters of the display were identical to those used to measure electrophysiological contrast thresholds.

### Results

**Threshold Estimation**

The result from a single PERG trial is shown by the solid line in Figure 2. The integrated output (voltage).

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* We found that the PERG had a similar contrast threshold, whether contrast was increased from 0.1–20% or decreased from 20–0.1%. In comparison, the VEP showed a strong adaptation effect under these conditions; the contrast thresholds obtained were higher for trials in which contrast was decreased than for those in which contrast was increased.
of one phase channel is plotted as a function of stimulus contrast. At the beginning of the visually driven activity, the output begins to rise. A zero response amplitude point is thereby defined, and serves as the baseline for extrapolation (horizontal dashed line). The electrophysiological contrast threshold is estimated by extrapolating the amplitude slope (slanted dashed line) back to the baseline. The straight line was fit by eye to the amplitude slope. Previous work has demonstrated that the contrast threshold thus determined is invariant over a wide range of starting voltages. In addition, contrast threshold estimates are not affected by changes of amplitude slope (see Fig. 6 of Ref. 22). Other examples using these methods have been previously published.

**Temporal CSFs**

Figure 3 presents mean PERG (open circles) and mean psychophysical (×) temporal CSFs for a 1.0 cpd sine-wave grating. Error bars represent plus and minus one standard deviation. Where omitted, the error bar is smaller than the plotted point. The peak PERG sensitivity occurred at 5 alt/sec for both subjects; sensitivity decreased at higher and lower alternation rates. The psychophysical temporal CSF, however, had a low-pass pattern; the corner frequency of the high frequency roll-off was between 15 and 25 alt/sec. The VEP temporal CSF was also determined under these same conditions. Figure 4 presents mean VEP (open triangles) and mean psychophysical (×) temporal CSFs for a 1.0 cpd sine-wave grating. The shape of the VEP temporal CSF closely resembled that determined psychophysically, although with a constant (approximately 0.3 log unit) loss of sensitivity across temporal frequency. Using these methods, a similar loss in VEP sensitivity relative to psychophysical sensitivity has been reported across spatial frequency.

**Spatial CSFs**

Figure 5 presents mean PERG (open circles) and mean psychophysical (×) spatial CSFs for both subjects.
Discussion

Temporal CSF

There is little resemblance between the PERG and psychophysical CSFs across temporal frequency. The psychophysical temporal CSF had a low-pass pattern, as noted previously in investigations using stimuli of similar spatial frequency.28,29 The PERG temporal CSF, on the other hand, had a band-pass characteristic.

There is little reason to expect agreement between the PERG and psychophysical temporal CSFs. Whereas little reorganization occurs between the retina and the lateral geniculate nucleus (LGN) of the cat in the spatial domain,30 it does take place in the temporal domain. The band-pass response characteristic of cat retinal ganglion cells31,32 is not seen in cat cortical units (area 17) which are reported to be low-pass.33 In agreement
with response functions shown by cortical elements, the human VEP temporal CSF is also low-pass (Fig. 4), and serves as an accurate predictor of the shape of the psychophysical temporal CSF.

The close agreement in shape of the VEP and psychophysical temporal CSFs agrees with the results of Sternheim and Cavonius, who estimated VEP (and PERG) contrast threshold by extrapolating the amplitude/contrast function to zero amplitude for a set of stimuli differing only in temporal frequency, and complements the agreement shown across spatial frequency. A comparison of these threshold temporal CSFs with suprathreshold VEP amplitudes measured across temporal frequency shows little agreement. At suprathreshold contrast levels, human VEPs show narrow temporal frequency tuning. Monkey VEPs also show this pattern. The human VEP saturates at moderate levels of contrast, as does the contrast response function of single cortical neurons in monkey. This must underly the distortion of the suprathreshold temporal frequency function. Determining how the VEP amplitude/temporal frequency function depends upon contrast at suprathreshold levels is a research area that requires further study.

The present PERG results generally agree with those of Sternheim and Cavonius. They also found that the PERG temporal CSF was band-pass, while the psychophysical and VEP temporal CSFs were both low-pass. However, Sternheim and Cavonius found the PERG temporal CSF to peak at a slightly higher temporal frequency (10 alt/sec; 5 Hz) than we found here. The observed difference may be due to their use of a brighter and chromatic field. Since only this study and the present one have examined the PERG temporal CSF, resolution of this difference requires further research.

Experiments using suprathreshold stimuli have shown the PERG to have an amplitude peak at a slightly higher temporal frequency. It is interesting to note that, across studies, the amplitude function appears to peak at a higher temporal frequency at higher contrast levels. These findings are similar to those reported for cat retinal ganglion cell response reorganization with increasing stimulus contrast.

Spatial CSF

The PERG spatial CSF peaked at a lower spatial frequency than did the psychophysical CSF. This difference may be due to the retinal location of the objective measurement. The PERG is elicited fairly uniformly across the retinal area of our stimulus. Psychophysical contrast sensitivity, for most spatial frequencies, falls off rapidly with increasing eccentricity, when target size is held constant. Because threshold is determined by the most sensitive part of the retina, the spatial CSF determined psychophysically represents mainly foveal and parafoveal function. Since the PERG represents more equally the entire stimulus field, including those areas in which cells have larger receptive fields, then the PERG spatial CSF should peak at a lower spatial frequency than the psychophysical CSF.

Korth et al. reported PERG spatial CSFs developed using a criterion amplitude approach. In contrast to the results of our study, they demonstrated a sensitivity peak at about 4 cpd for both the PERG and psychophysical spatial CSFs. This disparity of results may be attributable to the difference in mean stimulus luminance used in the two studies. Korth and Rix showed that the peak of the pattern-onset and pattern-offset PERG amplitude vs spatial frequency function shifted from about 0.3 cpd to about 2–3 cpd when mean luminance was increased from 457 to 50119 photopic td. Therefore, the difference in mean luminance between our stimulus and the brighter one of Korth et al. may explain the variation of the peak of the spatial CSF. A complication is that Korth et al. used pattern reversal stimulation, as we did here, which may not yield results identical to those obtained with pattern-onset-offset stimulation. Furthermore, with only two points, many results could be fitted with these data. Clearly, the present results are not discrepant with these trends, and we offer the results of Korth and Rix as a possible explanation for the difference in peak spatial frequency between the present spatial CSF and that of Korth et al.

The reason why Korth et al. found a higher degree of similarity between their PERG and psychophysical spatial CSFs than shown in the present results remains unclear. They measured the psychophysical CSF with a stimulus that differed both in luminance and area from that used to evoke the PERG; strictly speaking, their functions are not comparable. We measured PERG and psychophysical spatial CSFs under the same stimulation conditions, and found that the two functions are not identical.

The shape of the PERG amplitude vs spatial frequency function is controversial. Over the same spatial frequency range, the amplitude of the human PERG has been found to increase monotonically with decreasing spatial frequency, to be band-pass, or to be low-pass across spatial frequency. These differences may vary according to suprathreshold contrast conditions. In the present study, we have used a threshold measurement of retinal func-
tion. Given the wide variety of results from apparently similar experiments using stimuli of high contrast, and the possibility of stray light artifacts when using such stimuli, the measurement of PERG threshold may yield more consistent information among laboratories than that of PERG amplitude.

Methodological Considerations

An electrophysiological contrast threshold can be estimated several times within a few minutes using a swept stimulus lock-in amplifier retrieval method. When using conventional signal averaging methods, a threshold estimate can be developed only once from the work of many minutes. Besides the advantage of speed, the swept stimulus method also allows estimates of threshold variability. As a result, the contrast sensitivity of the PERG can be assessed in great detail for many stimulus conditions, which would be important for identifying and understanding the elements underlying this retinal response.

Key words: pattern electroretinogram (PERG), contrast threshold, contrast sensitivity, temporal frequency, spatial frequency

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References

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