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Computation of the luminance and pattern components of the bar pattern electroretinogram

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Abstract. Pattern onset electroretinograms (PERGs) were recorded from four normal subjects. Square-wave gratings of 75% contrast were presented in three approximately contiguous, concentric zones of outer angular radius, 5.1°, 12.6°, and 23.6°. The zones were calculated to give equal numbers of ganglion cell receptive fields. The recorded PERGs were considered to include luminance and pattern components which have low and bandpass spatial tuning functions respectively. These components combine in the PERG to produce a broad spatial tuning characteristic. The amplitude of PERGs in response to low spatial frequency stimuli is widely reported to be linearly related to contrast. The retinal illuminance response at every spatial frequency was computed from the eye's modulation transfer function. This function characterizes the reduction in contrast that occurs because of optical degradation. The computed retinal illuminance response was subtracted from the PERG waveform and a pattern-specific response was revealed. The latter had a highly tuned bandpass function which peaked at higher spatial frequencies than the PERG at corresponding peripheral angles.

Introduction

It has been proposed that the pattern electroretinogram (PERG) represents the summation of localized responses to luminance changes across the retina (Spekreijse et al., 1973; Riemslag et al., 1985). The PERG would therefore share the same locus and mode of generation as the conventional flash ERG, which is believed to arise via a distal generator producing ionic currents in the Muller cells (Ripps and Witkovsky, 1985). Intraretinal recordings and lesioning studies in animals, however, suggest that the PERG has a more proximal retinal generator (Maffei and Fiorentini, 1981; Holden and Vaegan, 1983). Indeed the ganglion cell layer has been specifically mooted as the PERG generator, because the time course of the PERG amplitude reduction after optic nerve section closely follows that of retrograde degeneration (Maffei et al., 1985). The focal light ERG is reported to be unaffected in these cases, although it is noteworthy that retrograde degeneration can also affect the physiology of the inner retinal layers (Dawson et al., 1986).

Under certain experimental conditions the PERG has also been shown to have a bandpass spatial selectivity (Arden and Vaegan, 1983; Hess and Baker, 1984; Teping and Groneberg, 1984). Such a property has been related to pattern processing by spatially antagonistic receptive fields (Padmos et al., 1973) and has been regarded as support of ganglion cell involvement in PERG generation (Odom and Norcia, 1984).

This study has been designed to extract the response to local luminance change from the pattern onset ERG recorded to a black and white square-wave grating. The proportion of luminance response evoked by the grating pattern is estimated and subtracted from the recorded PERG. Any additional response in the PERG signal related to the spatial content of the pattern would then be revealed as the residual waveform.

Materials and method

The pattern ERGs were recorded with vertically oriented square-wave gratings of 75% contrast and spatial frequencies ranging 0.14–20 cpd. The black and white grating pattern was presented on a back projection screen (Drasdo, 1982) for 105 ms followed by a uniform field of mean luminance for 106 ms. The surround and room luminance were maintained at least 10% of the mean screen luminance level of 250 cd m^{-2} (Brindley and West-heimer, 1965). Responses were obtained from three contiguous zones that provided a central field of 5.1° radius, a mid-peripheral field of 5.6°–12.6° annular radii, and a peripheral field of 12.3°–26.3° annular radii. In order to obtain these fields the viewing distance was decreased from 126 cm to 50 cm to 25 cm respectively. Four normal volunteer subjects who were capable of steady fixation and 6/5 acuity participated in the study, wearing spectacle corrections when appropriate. A Dawson-Trick-Litzkow (DTL) fiber electrode was positioned in the lower fornix and referenced to an Ag electrode placed on the ipsilateral temple. An Ag electrode on the forehead served as a ground. The recordings were made binocularly except for the most peripherally presented stimuli. An interrupt button was introduced so that the subject could prevent averaging when blinking or fatigued. Averages of at least 100 responses for each stimulus condition were collected on a Nicolet Pathfinder 2 with a bandpass of 5–70 Hz. The data were stored on magnetic media for subsequent processing.

A luminance-driven response would be expected to relate to the change in luminance with time, i.e. the temporal contrast of the stimulus, while a pattern-driven response would relate to the spatial contrast. Both may be defined by the Michelson equation:

$$C = L_{max} - L_{min}/L_{max} + L_{min}$$

When a pattern is phase-reversed the spatial contrast of the stimulus is equivalent to its temporal contrast. However, when a pattern is presented in an onset/offset mode the spatial contrast differs from the temporal contrast. The spatial contrast is the same as in the phase reversal condition, but the temporal contrast of a pattern element appearing from a background of mean space-averaged luminance is not the same as the temporal contrast of an element disappearing into the background. This method of presentation thus produces a nonlinearity in the space-averaged temporal contrast. The contrast of the retinal image is reduced at high spatial frequencies because of optical degradation and light scatter within the eye. This degradation is characterized by the eye's modulation transfer function. This function is reported to be fairly constant within a central 25° radius (Jennings and Charman, 1981). An estimate of the modulation transfer function was taken from the data of Campbell and Gubisch (1966) which could be approximated by the following equation:

$$M = \exp - (f/8.4)^{0.8}$$

M is the modulation amplitude and f is the spatial frequency in cpd. This expression was chosen because it relates to the group-averaged measurements of three subjects made in white light with a pupil size of 4.9 mm, close to our sample's mean of 5 mm.

The first 99 harmonics that make up a square-wave grating were each filtered by this modulation equation. The filtered harmonics were then used to synthesize an illuminance profile of the square-wave as it would appear on the retina after it has passed through the optics of the eye. A series of illuminance profiles were obtained in this way for a range of spatial frequencies (Fig. 1). These retinal illuminance profiles thus differ from the luminance profiles of the external stimulus and it is therefore appropriate to refer to the retinal illuminance response rather than the luminance response.

The amount of contrast attenuation caused by the scattered light was computed from the illuminance profile of each grating spatial frequency used. The space-averaged temporal contrast of each stimulus spatial frequency was calculated for the pattern onset/offset mode of presentation. In a previous report (Drasdo et al., 1987) it had been assumed that the contrast reduction was proportional to the area of the synthesized square-wave grating, i.e. the retinal illuminance profile. This is indeed the case for the phased-reversed square-wave. However the nonlinearity in the contrast stimulation elicited by pattern appearance/disappearance makes it necessary
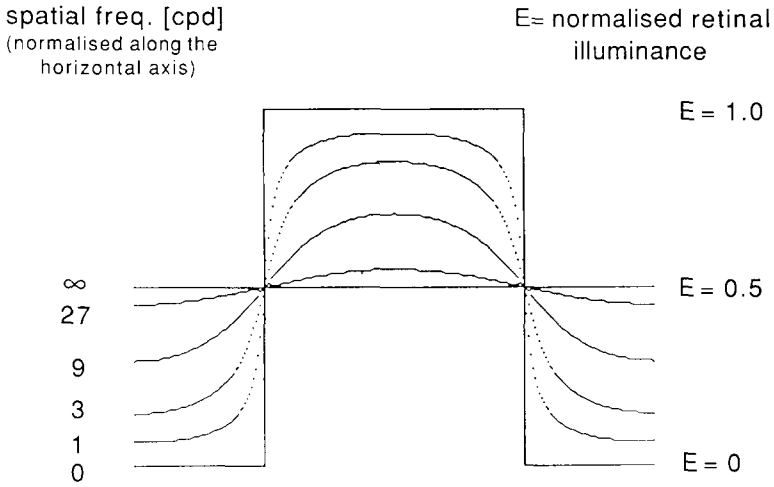
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spatial freq. [cpd]
(normalised along the horizontal axis)

E= normalised retinal illuminance

E = 1.0

∞
27

9

3

1
0

E = 0.5

E = 0

Fig. 1. Retinal illuminance profiles for square-wave gratings synthesized from their filtered Fourier components.

to calculate the temporal contrast at every point on the illuminance profile for both an appearing element and a disappearing element (which have different temporal contrasts) before taking an average. The resulting space-averaged temporal contrast for each spatial frequency was divided by the temporal contrast of an unattenuated square-wave of the same spatial frequency in order to obtain a contrast attenuation factor. A normalized function describing the variation of the attenuation factor with spatial frequency for square-wave gratings of 75% screen contrast is shown in Fig. 2.
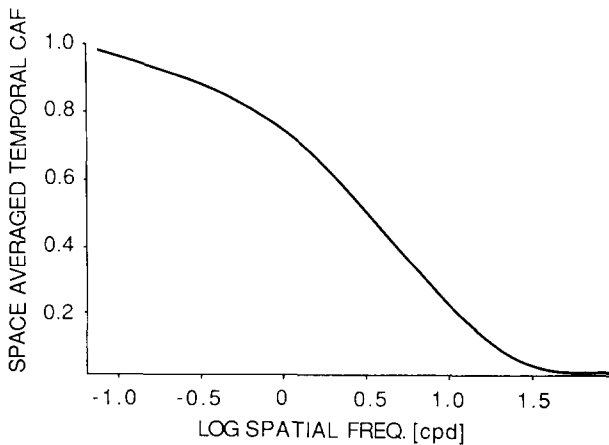
Fig. 2. Normalized function showing the change in the temporal contrast attenuation factor (CAF) with spatial frequency for square-wave gratings of 75% contrast.

The PERG has been shown, at the best approximation, to be linearly related to contrast (Korth and Rix, 1984, pattern onset/offset; Hess and Baker, 1984; Arden et al., 1982; Korth and Rix, 1985, pattern reversal). Therefore the response amplitude to retinal illuminance changes evoked by gratings of higher spatial frequencies might be expected to be directly related to the attenuation of temporal contrast. The PERG in response to low spatial frequencies (or local ERG in the ultimate case of one element modulating in the entire screen) also has a linear relationship with contrast (Korth and Rix, 1984; Hess et al., 1986). The low spatial content of the stimulus means the response must be dominated by illuminance processing. When this response is multiplied by the correct contrast attenuation factor, the amount of illuminance response at higher spatial frequencies can be computed. If the computed retinal illuminance response for a given bar width is subtracted from the PERG recorded to the same bar width, any residual waveform (other than to local illuminance) will represent additional processing. This procedure of subtraction was therefore applied to the PERG data for each bar width in the different retinal zones.

Results

The data of four subjects (eight eyes) were group-averaged for the three stimulus fields. The responses from the most peripheral region were the largest and best defined, those from the central region smallest, and those from the mid-peripheral zone of intermediate amplitude and quality.

The negative-going transients of the onset PERGs demonstrate a very broad tuning function with spatial frequency, with a slight attenuation at low spatial frequency. This is best illustrated by the graph taken from the mid peripheral zone relating the onset response amplitude to spatial frequency (Figs. 3 and 4). Positivity is shown as an upward deflection. The offset responses show a monotonic amplitude decrease with increasing spatial frequency (Arden and Vaegan, 1982; Korth, 1983).

The pattern ERGs from the central and peripheral field are shown in Figs. 5 and 6. The first column shows the group-averaged recorded PERG waveforms for the eight eyes to a range of spatial frequencies. The second column shows the computed retinal illuminance response appropriate for each spatial frequency. The retinal illuminance response was derived from the lowest spatial frequency response recorded in each zone – central − 0.76 cpd, mid-periphery − 0.30 cpd, and peripheral zone 0.14 cpd. For purposes of calculation these were assumed to represent only illuminance processing. Therefore these low spatial frequency waveforms are multiplied
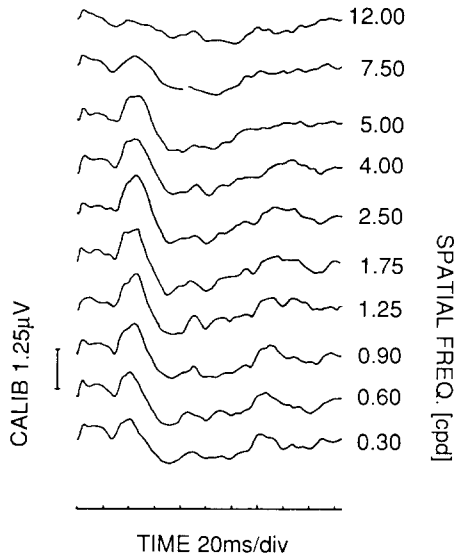
Fig. 3. Group-averaged PERGs recorded from the mid-peripheral stimulus field.
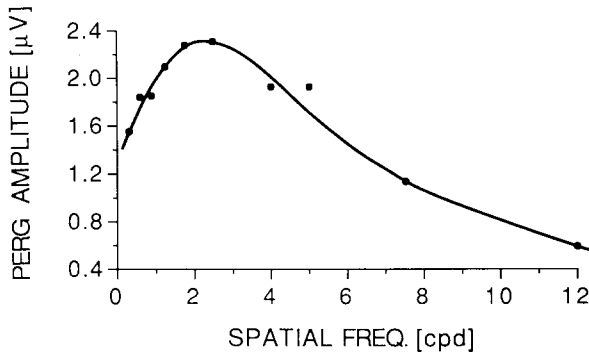

Fig. 4. Spatial tuning of the raw PERG from the mid-peripheral field; the amplitude of the negative transient of the onset responses are displayed graphically as a function of spatial frequency.

by the appropriate contrast attenuation factors for the higher spatial frequencies. The contrast attenuation factors are taken from the graph in Fig. 2 for pattern onset/offset square-wave gratings of 75% contrast. In this way the proportion of the response to illuminance contained in each waveform is obtained.

The final process is the subtraction of the retinal illuminance response from the raw PERG data. In our experiments we have been unable to find any systematic latency variation of low spatial frequency PERGs at different contrast levels, and therefore the subtraction was undertaken at a fixed
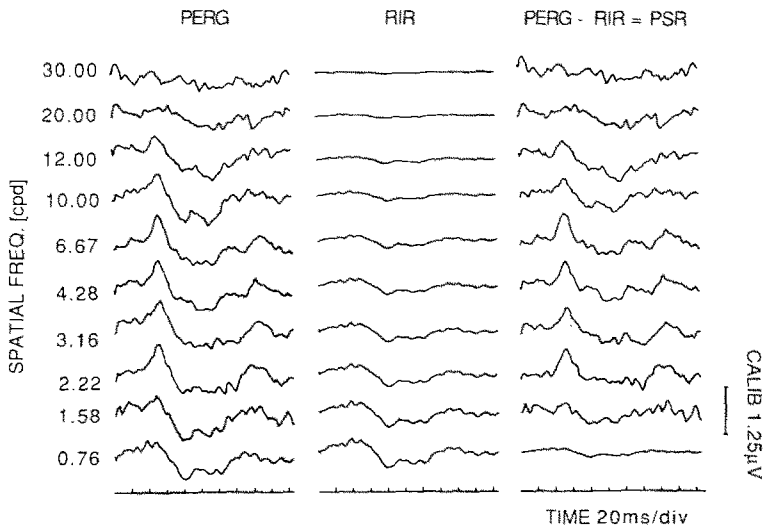
Fig. 5. Group-averaged data for the central 10° diameter field shows the result of the subtracting the retinal illuminance response (RIR) from the recorded PERG. The extracted pattern-specific response (PSR) is shown in the third column.
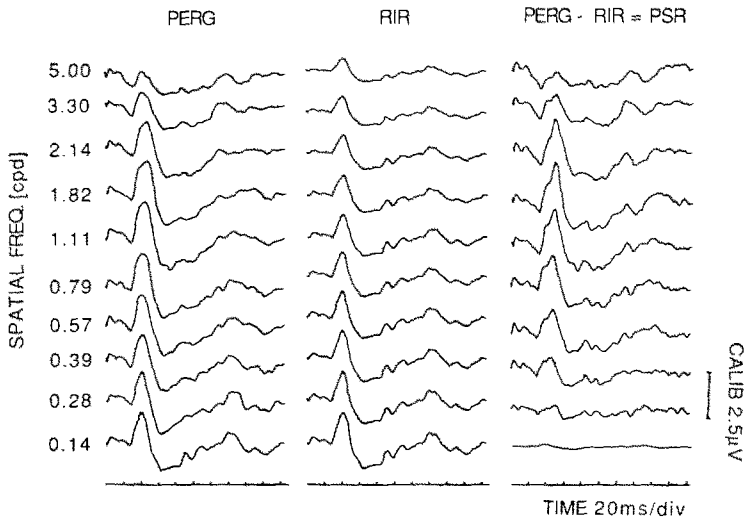

Fig. 6. Group-averaged data for the peripheral annulus (r = 12.3–23.6°), showing larger, better defined PERGs. These are processed in the same way as the data from the central field to reveal a pattern-specific response.

latency. Indeed it appears from the data of Korth and Rix (1984) that reduced contrast does not alter the latency of the PERG to stimuli of low spatial frequency.

The result of the subtraction is displayed in the final column. The nature

of the subtraction reveals a more pronounced spatial tuning. The residual response is presumed to represent processing additional to illuminance processing – a pattern-specific process.

Discussion

The three contiguous zones examined with pattern onset/offset square-wave gratings produced pattern-specific responses of different peak spatial frequencies. The tuning peak occurred at lower spatial frequency with increasing eccentricity (Fig. 7). This is consistent with the idea of a retinal generator possessing a receptive field with center-surround antagonism, the dimensions of which increase with retinal eccentricity.

It has been argued that the PERG can be explained as the nonlinearities or second harmonics isolated by the method of stimulation (Holden and Vaegan, 1983; Baker and Hess, 1984). In a uniform field these nonlinearities have been proposed to have a common, possibly more proximal generator, but their spatial characteristics are masked by the large fundamental component (Hess et al., 1986).

The areas of the zones were originally calculated to contain equal ganglion cell densities (Drasdo 1977). If the ganglion cells played a major role in PERG generation, the resulting amplitude would have been anticipated to
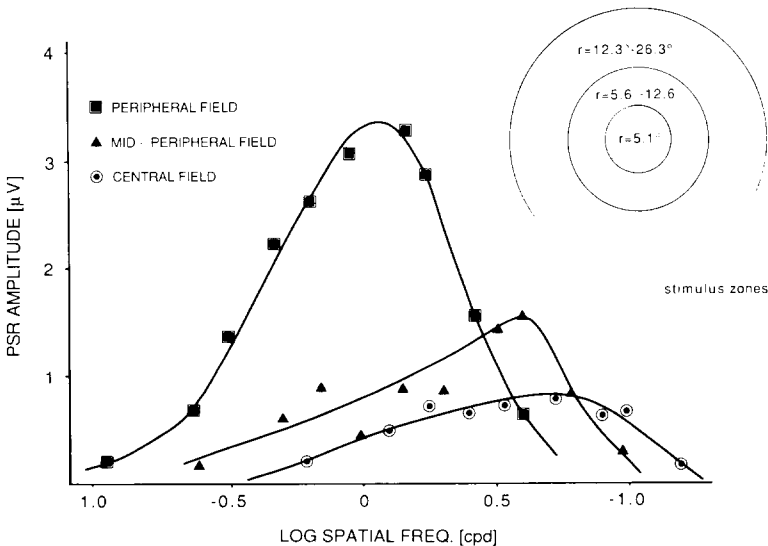

Fig. 7. Spatial tuning functions of the pattern-specific response for the three stimulus zones; peaking from left to right, peripheral to central fields at higher spatial frequencies.

be roughly proportional to the density. However the amplitude of the responses recorded from the peripheral region were noticeably larger than those recorded centrally. This could be the result of stimulating larger ganglion cells, which may generate larger responses; ganglion cell size is known to increase with eccentricity (Polyak, 1957). More probably it indicates that the response involves other types of retinal neurones as well as ganglion cells. This is consistent with the fact that the PERG shows a moderate degree of macular overrepresentation, as previously observed (Arden and Vaegan, 1983). This is shown in Fig. 8. The function relating the angular area in each zone, required to give a criterion response to 1 μV to the mean angular eccentricity of each zone, may be fitted by a straight line.

It is also possible that the original estimate of ganglion cell density was inaccurate, the gradient of density with eccentricity being too steep. The most central value of ganglion cell density is very difficult to estimate because of the displacement of the ganglion cell bodies in the foveola (Rovamo, 1978).

Since it seems likely that the ganglion cells are not the sole generators of pattern-specific response, the role of other retinal neurones must be considered. Bipolar cells are more numerous (Missotten, 1974), and in addition to contributing to the light ERG, some have been reported to show a center-surround receptive field organization, which could contribute to spatial selectivity of the pattern-specific response (Werblin and Dowling, 1969). Riemslag and Heynen (1984) have reported that the current source depth of the PERG and the light ERG are localized in the bipolar layer.

The retinal illuminance response resulted from different retinal contrasts at different spatial frequencies. Similarly the pattern-specific responses did not arise from equal retinal contrasts. It could be argued therefore that similar correction factor should be applied to the pattern-specific response.
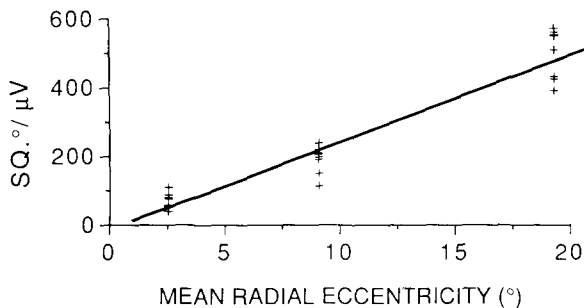

Fig. 8. Linear function relating the area required for a criterion response of 1 μV to the mean angular eccentricity of the stimulus zone. The correlation coefficients is 0.96 and the slope of the function is significant at the 1% level.

It is hypothesized that this response is related to the spatial contrast, whereas the retinal illuminance response is related to temporal contrast. If the pattern response can be shown to be linearly related to spatial contrast it might be appropriate to apply a correction based on the modulation transfer function. Future work on statistical assessment pattern-specific response amplitude, peak spatial frequency, and receptive field sizes with eccentricity might then correlate more significantly with specific retinal cell populations.

There are several assumptions inherent in the method described. No account was taken of the phase transfer function, because no data are available for white light. However even with monochromatic light its random tendencies and wide interindividual variation (Walsh and Charman, 1985) are likely to cancel any error induced in the modulation transfer function estimate.

Our own experimental observations together with other investigators, most notably Korth and Rix (1984), confirm the assumed linearity of the low spatial frequency PERG with contrast. However we recognized the limitation imposed by the available series of grating spatial frequencies on which the retinal illuminance contribution was based. The grating series did not provide the ultimately limiting spatial frequency commensurate with a pure luminance response. The difference was considered to be insignificant in relation to experimental error. Our observations of low spatial frequency PERGs have not shown a consistent or systematic latency change with reduced contrasts. This appears to agree with the work of Korth and Rix (1984).

Conclusions

The evaluation of the retinal response to illuminance and its subtraction from the recorded PERG reveals a residual response that demonstrates a pronounced spatial tuning. Consideration of the contrast attenuation caused by optical degradation provides an effective method for the separation of illuminance and pattern responses contained in the recorded PERG signal.

The pronounced spatial tuning that results from this technique strengthens the suggestion of a contribution to the PERG signal from retinal generators with spatially antagonistic receptive fields. The present refinement of the technique, however, does not allow the locus of PERG generation to be labelled more specifically. It is anticipated that improvements in the method will provide a means of further elucidating the origin of the PERG.

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