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Influence of Eccentricity on Short-Wavelength Pathway Isolation in Automated Perimetry

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ABSTRACT

Purpose : To evaluate mechanisms detected by short-wavelength automated perimetry (SWAP) using a two-channel Maxwellian view optical system.

Methods : We measured spectral sensitivity and threshold-versus-intensity (tvi) curves. Three types of background were used : white light, 568-nm monochromatic light, and yellow light obtained with the OG530 filter used in SWAP. When spectral sensitivity was measured, interference filters were used as stimuli, and the brightness of the background was 1,000 photopic trolands. For tvi curves, 440-nm monochromatic light was used as the stimulus.

Results : The measurement of spectral sensitivity using each background showed 3 phases. On the short-wavelength side, short-wavelength-sensitive cone responses were detected. The tvi curves revealed rod pathway responses, followed by Stiles $\pi 1$ and $\pi 3$ mechanisms at eccentric sites. When the background brightness was 1,000 photopic trolands, the $\pi 1$ mechanism was detected at eccentric 4° and 8° and the $\pi 3$ mechanism was detected at 12°.

Conclusion : The background light used in SWAP is adequate for detecting short-wavelength-sensitive cone responses. However, depending on the measurement site and retinal illuminance, the detected mechanism was $\pi 1$ and not $\pi 3$. These findings suggest that different short-wavelength-sensitive cone responses are detected according to measurement sites.

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Key words : short-wavelength automated perimetry, Stiles π mechanisms, spectral sensitivity, threshold-versus-intensity curves, short-wavelength cone

INTRODUCTION

To isolate and measure responses of individual cone pathways of the retina, responses of 2 of the 3 cone types (long-, middle-, and short-wavelength-sensitive cones) should be suppressed by selecting the brightness and color of the background and test stimulus. Various measurement methods have been used. Stiles established the two-color threshold approach in which the threshold of a monochromatic stimulus presented on a monochromatic background is measured using a two-channel Maxwellian view optical system[1]. This method is theoretically ideal but is also time-consuming and requires a light source emitting an adequate quantity of light, because mono chromatic light obtained with narrow-band (8 nm half-band width) interference filters is used. Therefore, applying this method in general clinical practice has been difficult. Wald[2] reported that responses of each cone can be evaluated by a selective chromatic adaptation technique in which the increment threshold is measured using wide-band filters for background

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light. This method is less time-consuming than the two-color threshold approach and, therefore, has been used clinically. However, theoretical analysis with this method is difficult owing to the wide band of the background light and because the pattern of the spectral sensitivity curves changes with background intensity[2]. In addition, when these methods are applied to perimetry, suppression of both the responses of the long- and middle-wavelength-sensitive cone pathways and of the rod pathway, which requires a high-luminance background, is important. Thus, to isolate short-wavelength-sensitive cone responses, perimetry requires a yellow background with markedly higher retinal illuminance and an intense light source because of the use of narrow-band interference filters for a blue stimulus. However, on the background used in perimetry, the quantity of light from the source is restricted and markedly decreases owing to the use of a reflector plate. Therefore, to develop perimetry for the detection of short-wavelength-sensitive cone responses, Wald's selective chromatic adaptation technique has been used[3,4].

For clinical perimetry that measures short-wavelength-sensitive cone responses using a high-luminance yellow background, short-wavelength automated perimetry (SWAP) as a function of the Humphrey Field Analyzer (HFA : Carl Zeiss Meditec, Dublin, CA, USA) was developed. In SWAP, to obtain a high-luminance yellow background, luminance was determined to be 100 cd/m² using 530-nm cut-off filters (OG530, Schott North America, Elmsford, NY, USA) as yellow filters interrupt light at a wavelength of 530 nm or less. For the stimulus, blue interference filters with a peak wavelength of 440 nm and a half-band width of 27 nm were used. The presentation time was 200 milliseconds, and the target size was Goldmann V. To determine the background and stimulus in SWAP, threshold-versus-intensity (tvi) curves were obtained using an HFA, and the optimal conditions for the isolation of short-wavelength-sensitive cone responses were selected[5].

To evaluate detailed mechanisms measured by SWAP based on Wald's selective chromatic adaptation technique, the results of SWAP were compared with those of Stiles' two-color threshold approach. First, using narrow-band interference filters for the background and stimulus, spectral sensitivity curves and tvi curves were obtained using a Maxwellian view optical system. Stiles π mechanisms were measured, and the results were compared with those obtained using the yellow background in SWAP. With the Stiles π mechanisms, spectral sensitivity at all wavelengths from short to long is expressed as the capital letter Π, and that in the tvi curves is expressed as the small letter π.

Experiment Methods

The subjects were three healthy volunteers without eye disease (age, 30 to 34 years). A two-channel Maxwellian view optical system with a xenon lamp (150 W) light source was used for measurement. The visual angle of the background light was 8°, and that of the stimulus light was 1° with a stimulus lasting 200 milliseconds. The quantities of background light and stimulus light in each experiment were measured with a Silicon Photo Diode S2281 (United Detection Technology, Hawthorne, CA, USA) and a Photo Sensor Amp C1837 (Hamamatsu Photonics, Hamamatsu, Japan).

1. Spectral sensitivity using a yellow or white background

Spectral sensitivity was measured with interference filters having a half-band width of 6 nm at 10-nm intervals from 400 to 700 nm. In addition to a white light background, yellow backgrounds obtained with the OG530 yellow filter (Schott) used in SWAP and interference filters with a peak wavelength of 568 nm and a half-band width of 6 nm (568 nm background) were used. The brightness of the background light was 1,000 photopic trolands (TP), which corresponds to retinal illuminance with a pupil diameter of 3.5 mm at a luminance of 100 cd/m². Measurement was performed at the central fovea and retinal temporal 4° and 8°. The retinal illuminance using the white background or the OG530 background was determined by brightness match with the 568-nm background.

Since Stiles Π mechanisms are the integration of results from the two-color threshold approach, in which the increment threshold of monochromatic stimulus light for monochromatic background light is measured, the estimated sensitivity of the mechanism to chromatic background light at an arbitrary brightness and wavelength can be obtained using its results. Figure 1 shows estimated sensitivity curves of Stiles Π mechanisms at a background wavelength of 570 nm and a brightness of 1,000 TP at the central fovea. When the threshold is measured, the point with the highest sensitivity for each wavelength on the graph is obtained. Therefore, under these conditions, Π1 may be detected on the short-wavelength side and Π4 and Π5 on the long-wavelength side[6].

2. Relationship between the threshold for the blue test light and background intensity

For the stimulus, interference filters with a peak wavelength of 440 nm and a half-band width of 6 nm were used. For yellow backgrounds, the OG530 filter and 568-nm monochromatic lights were used. The tvi curves at the central fovea and retinal temporal 4°, 8°, and 12° were measured. The tvi curves were similarly measured with the white background. In the tvi curves, rod-pathway responses and cone-pathway responses were identified on the basis of the results of dark adaptation curves obtained the same day.

Results

1. Spectral sensitivity using a yellow/white background

Figure 2 shows spectral sensitivity curves at the central fovea and retinal temporal 4° and 8° using each background (1,000 TP) in subject 1. The results of spectral sensitivity curves at each site were arbitrarily moved upward or downward to avoid overlap. At each retinal site, spectral sensitivity showed triphasic curves. The phase with a peak at 440 nm showing

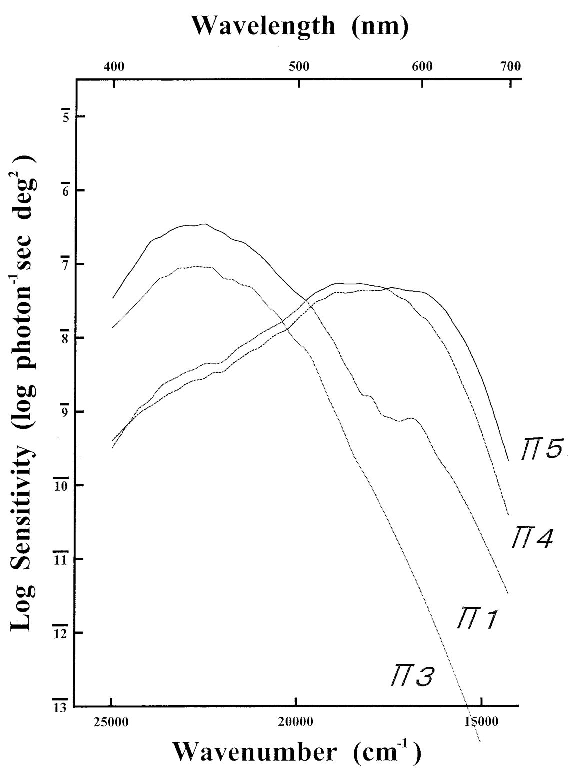

Fig. 1. Estimated values of spectral increment sensitivity of Π1,Π3,Π4, and Π5 at a background wavelength of 570 nm and a brightness of 1,000 TP. The horizontal axis indicates wave number and wavelength, and the vertical axis indicates the log of sensitivity.

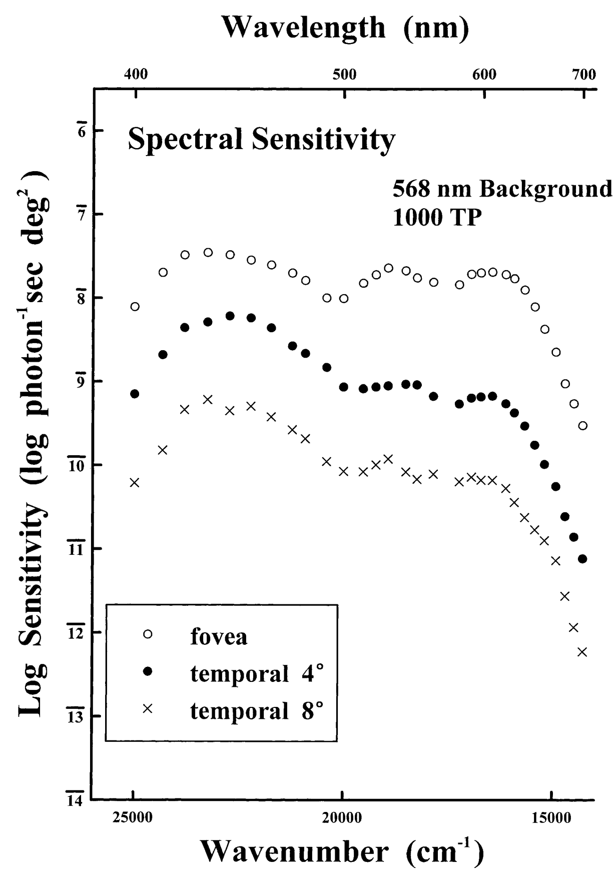

Fig. 2-a.

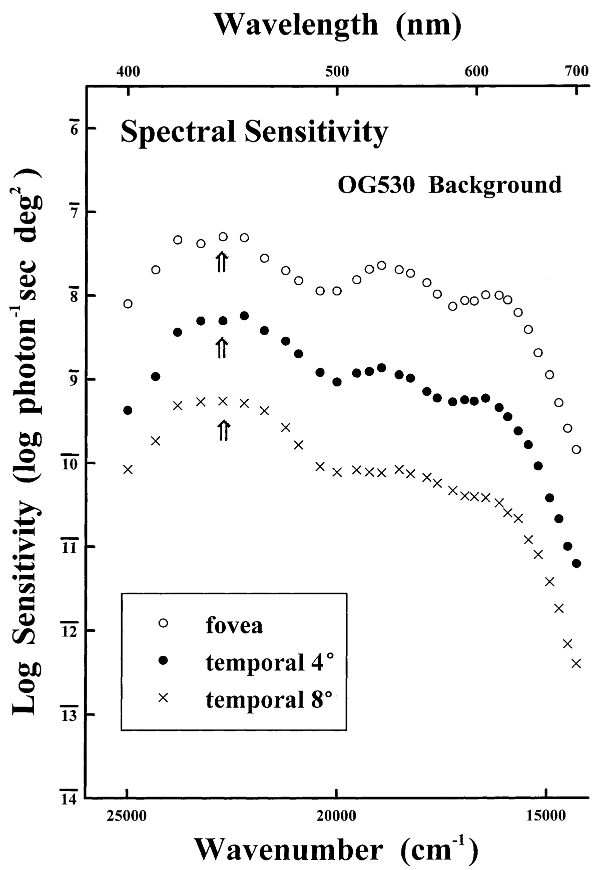

Fig. 2-b.

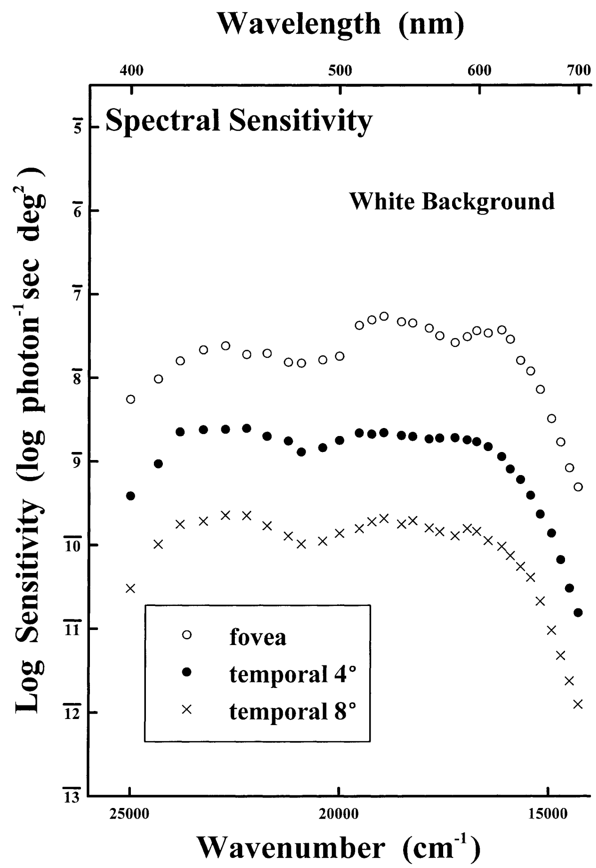

Fig. 2-c.

Fig. 2. Spectral sensitivity curves at the central fovea and retinal temporal 4° and 8° using each background at 1,000 TP in subject 1.
Figures 2-a, b, and c show spectral sensitivities using the 568-nm monochromatic background, the OG530 background, and the white background, respectively.

the highest sensitivity represents short-wavelength-sensitive cone responses, and the two phases with peaks at 530 nm and 610 nm, respectively, represent red-green chromatic opponent-response functions. When the test light had a wavelength shorter than 480 nm, short-wavelength-sensitive cone responses were detected. Similar results were obtained in subjects 2 and 3.

2. Relationship between the threshold for the blue test light and background intensity

Figure 3 shows tvi and dark adaptation curves using a 440-nm stimulus presented on the OG530 background that were obtained at retinal temporal 4° on the same day in subject 1. The dark adaptation curves suggest that the lower mechanism represents rod-pathway responses and that the mechanism approximated by the upper 2 curves represents cone-pathway responses.

Figures 4-a and 4-b show tvi curves using each background at retinal temporal 4° and 8°, respectively. Using the white background, cone-pathway components were approximated by one curve, and one mechanism consisting of chromatic opponent-responses was detected. Using the OG530 background, cone-system components were approximated by two curves, and two mechanisms were detected. The threshold with the 568-nm monochromatic background suggests that the two mechanisms correspond to Stiles $\pi 1$ and $\pi 3$. The lower curve may represent the $\pi 1$ mechanism, and the upper curve may represent the $\pi 3$ mechanism.

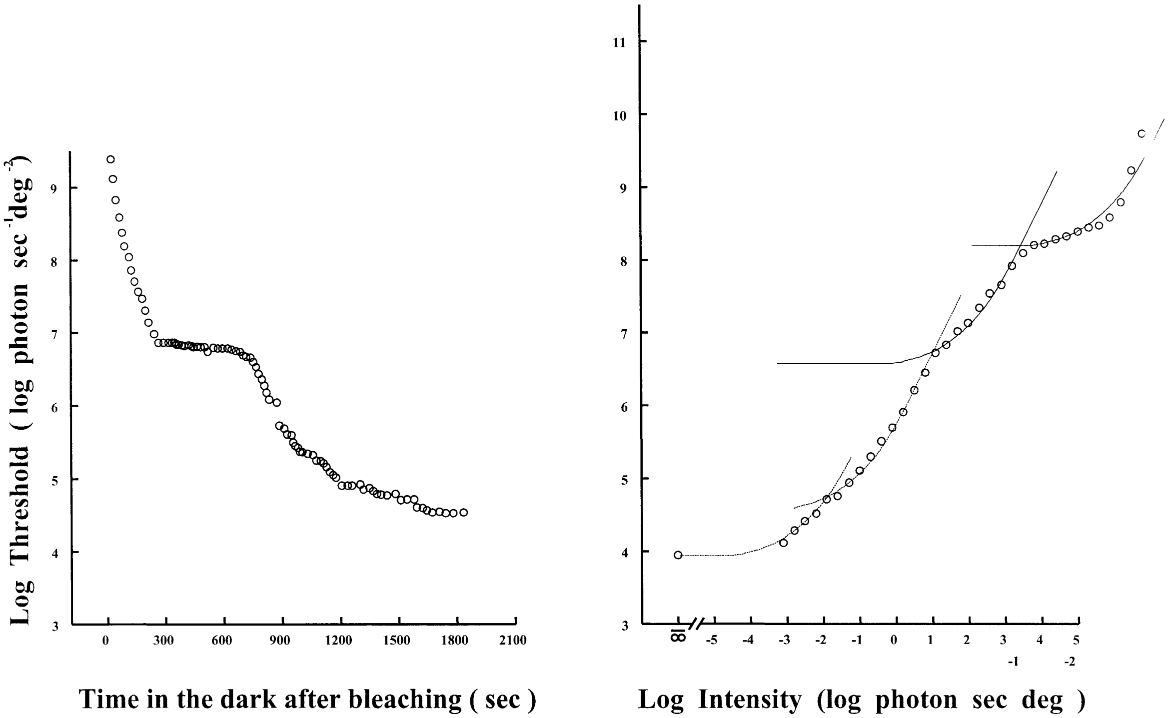

Fig. 3. The tvi curves using a 440-nm stimulus and the OG530 background, and dark adaptation curves using a 440-nm stimulus at retinal temporal 4° which were obtained on the same day in subject 1.

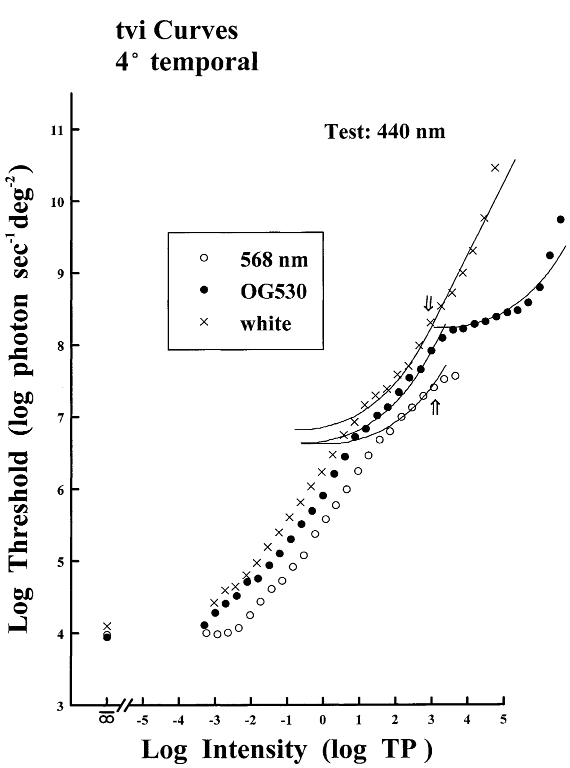

Fig. 4-a.

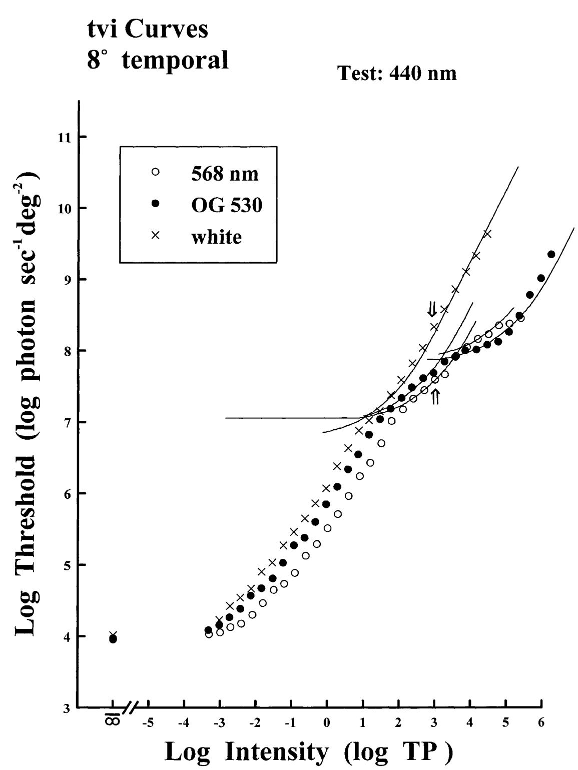

Fig. 4-b.

Fig. 4. The tvi curves using each background in subject 1.
Figures 4-a and b show tvi curves at retinal temporal 4° and 8°, respectively.

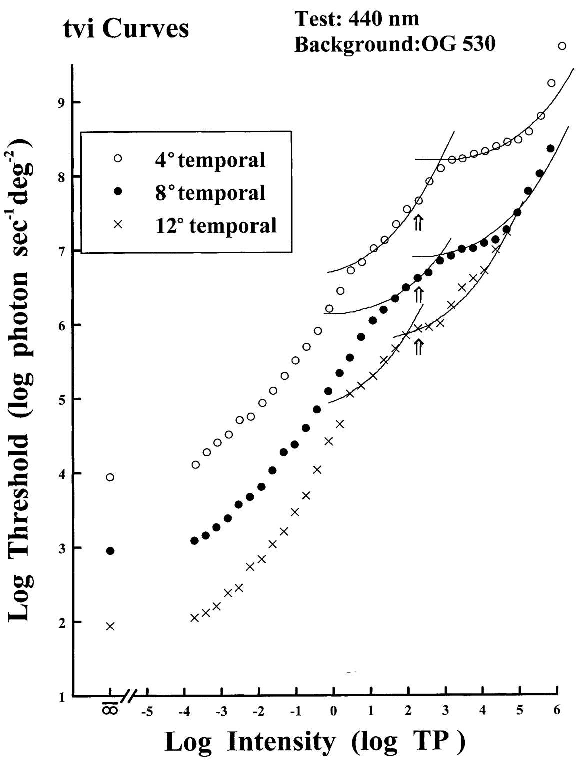

Fig. 5. The tvi curves using the OG530 background at retinal temporal 4°, 8°, and 12° in subject 1.

Figure 5 shows tvi curves at each eccentric site using the OG530 background. Results at each site were arbitrarily moved upward or downward. At eccentric sites, the rod-pathway mechanism was detected, followed by the $\pi1$ and $\pi3$ mechanisms as cone-pathway mechanisms.

Discussion

The relationship between the dark adaptation state and the response mechanism is expressed by tvi curves representing the relationship between the intensity of background light and the threshold for stimulus light. Stiles isolated various mechanisms from tvi curves and termed the rod system responses the $\pi0$ mechanism, middle-wavelength-sensitive cone responsesas the $\pi4$ mechanism, and long-wavelength-sensitive cone responses the $\pi5$ mechanism. In addition, Stiles showed that there are $\pi1$, $\pi2$, and $\pi3$ mechanisms for short-wavelength-sensitive cone responses, suggesting that the $\pi3$ mechanism is the pure mechanism for responses of this pathway[1]. Therefore, to detect short-wavelength-sensitive cone responses, the optimal background intensity allows the detection of the $\pi3$ mechanism. In the present study, the results of spectral sensitivity using the OG530 background at 1,000 TP showed a triphasic pattern at the central fovea. Toward the temporal side from the center, red-green chromatic opponent-response functions were less frequently detected, whereas short-wavelength-sensitive cone responses were definitely detected without changes.

The estimated values in Fig. 1 and the results using the 568-nm monochromatic background suggest the $\Pi1$ mechanism of short-wavelength-sensitive cone responses. In tvi curves, at eccentric sites, the $\pi0$ mechanism was detected, followed by short-wavelength-sensitive cone responses. Using the yellow background, $\pi1$ was detected, followed by $\pi3$ as cone system responses. At 1,000 TP, the detected mechanism changed from $\pi1$ to $\pi3$ at more-eccentric sites. Thus, the $\pi1$ mechanism was mainly detected by SWAP when the pupil diameter was about 3.5 mm, and the $\pi3$ mechanism may be involved in the eccentric area. However, retinal illuminance is affected by the pupil diameter or optic media even in healthy persons, and mechanisms detected by SWAP may be affected by individual differences in lens color or macular pigments[7-9]. In addition, when short-wavelength-sensitive cone responses decrease or disappear in various eye diseases, the thresholds of rod pathway responses and long- and middle-wavelength-sensitive cone responses may be affected. Studies have also suggested the possible detection of the luminance channel of short wavelength-sensitive cone responses when responses of this cone pathway are impaired[10,11]. Cubbidge et al. have reported that measuring tvi curves using perimetry with changes in the peak wavelength of blue interference filters and the half-band width used in SWAP is more useful for isolating short-wavelength-sensitive cone responses[12].

SWAP is an excellent means of detecting short-wavelength-sensitive cone responses and early abnormalities in diseases, such as glaucoma. However, it is important to evaluate abnormalities while considering the possibility that various elements may cause detected mechanisms to differ.

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