ELECTROSTIMULATION OF THE HUMAN EYE ADAPTED TO MONOCHROMATIC LIGHT, BY USING EXPONENTIALLY INCREASING CURRENT

MAKOTO SATO*

Physiological Laboratory, Iwate Medical College, Morioka, Iwate-ken, Japan

The accommodation process of the human retina to the electric current was first investigated by Motokawa and Iwama (3) by means of Hill's standard method using exponentially increasing currents as stimuli. Lately Sato, Suzuki and Akihamo (5) studied again in detail the accommodation of the human retina adapted to various intensity levels of white light, by using exponentially increasing currents with varying time-constant (RC) within a wide range from 0 to about 230 msec. They inferred that there would be within the retina two sorts of excitable tissues showing fast and slow accommodations, and that the one would be stimulated selectively by the increasing current of time-constant being shorter than 25 msec., and the other by that being longer than 90 msec.

Elaborating their experiment, I attempted to apply the experiment to the cases of the eye adapted to monochromatic lights of different wavelengths. The relationship between the electric threshold strength and the intensity of the adapting monochromatic light will be established precisely in this paper.

METHODS

A silver plate of 2×3 cm in size was used as a stimulating electrode and it was inserted between the upper lip and gum. Another large silver plate was placed under the sole of the right foot as an indifferent electrode, being immersed into 1% saline. Fig. 1 shows the circuit diagram for measuring the electric threshold of the eye. Taking the electrical phosphene as an index of excitation, the electric thresholds (V_f) for varying time-constants (RC) were measured, where V_f means the final voltage of the exponentially increasing current. The measuring procedure of the electric threshold (V_f) was the same as stated in previous paper (5).

The adapting lights of different wavelengths were selected through Lange's metal interference filters, and their intensities were varied not only by using several well cali-

FIG. 1. Circuit diagram for producing exponentially increasing current.

C: variable condenser (0-610 μF), E: battery (50 volts), K_1 : key, K_2 : contact key of pendulum, R_1 : 420 ohms, R_2 : 3,000 ohms, M: subject.

Received for publication October 12, 1957.

* 佐藤 誠

brated neutral tint filters of Matsuda SN-1 but also by a precise control of the supply voltage of the light source. For the details of the spectral transmittance of the interference filters I must refer the readers to Yaegashi's paper (8). The radiance (N) of the surface of a light source for every adapting light was measured by a system of a thermopile (sensitivity: 5.1 V per watt) and a galvanometer (sensitivity: deflection of 1 mm. at 1 m. per 10^{-8} V).

RESULTS

1) The relationship between the electric threshold (V_f) and the radiance (N)

Variations in the electric threshold (V_f) of the eye adapted to varying intensities of the radiance (N), namely V_f -log N curve, were investigated by using monochromatic rays with various wavelengths of 432, 463, 499, 550, 589 and 669 $m\mu$ as the adapting lights. It was found that the form of V_f -log N curve obtained was dependent not only on the wavelength of the adapting light but also on the time-constant (RC) of the stimulating current. Accordingly, the form of the V_f -log N curves for a given wavelength is dependent upon the time-constant of the stimulating current. Some examples for 550 and 669 $m\mu$ in wavelength were shown in fig. 2.

FIG. 2. Electric threshold strength-log-radiance relation. Numbers on the curves are time-constant of the current used. D: dark. (A) and (B) are two families of curves obtained with the eye adapted to monochromatic lights of 550 and 669 $m\mu$ in wavelength respectively.

Fig. 2 (A) shows that there are two different types of the V_f -log N curve depending on the different time-constant of the stimulating current, *i.e.*, the one is a group of the curves for time-constant shorter than 25 msec., while the other is a group of those for time-constant longer than 75 msec. The value of the electric threshold for shorter time-constant increases at first gradually with the increase in intensity of the adapting light from dark to 10^{-3} (relative unit), till it arrives at a maximum, then it decreases rapidly to reach a minimum at 10^{-1} unit, and then it increases again progressively with further increase in radiance. On the other hand, the electric threshold for time-constant longer than 75 msec. increases with increase in radiance (hereafter this part on the curve is called "left slope"), till it arrives at a certain value of V_f at which it is kept constant within a range between 10^{-4} and 10^{-3} unit (this part on the curve is called "horizontal section"). Again, a further increase in radiance causes the progressive rise in electric threshold (V_f) (this part on the curve is called "right slope").

As for the subjective impression of the electrical phosphene, two different characteristics were perceived according to whether the time-constant was long or short. The electrical phosphene for time-constant shorter than 25 msec. appears in a twinkle as a faint flash of light, while that for time-constant longer than 50 msec. appears with a gradual rise in intensity and disappears with a gradual fall. All these results are well consistent with those of our previous experiment performed with eye adapted to white light. Therefore, I concluded that the characteristics of the V_f -log N curve do not differ between the white light and the monochromatic ones, with an exception of 669 m μ .

Fig. 2 (B) illustrates the V_f -log N curves obtained for varying time-constants of the stimulating current under the adaptation to the monochromatic light of 669 m μ . As can be seen from comparison between fig. 2 (A) and fig. 2 (B), the curves for 669 m μ are something different in shape from those for 550 m μ , especially in the cases of the stimulating currents with time-constant longer than 75 msec. For instance, the upper two curves presented in fig. 2 (B) (curves connecting empty circles) run almost parallel to the horizontal axis within the range of radiance below 10^{-2} unit. In other words, these curves prove to have no "left slope", and that is the most remarkable difference from the curves for other shorter wavelengths. The value of the electric threshold (V_f) begins to increase abruptly, marking a clear break on the curve, as the radiance is raised over about 10^{-2} unit.

As regards the electric threshold for relatively longer time-constant, it must be noted that another lower threshold can be determined, when Motokawa's comparing procedure (4) is employed for determination of electric threshold. Thereby, the other V_f -log N curves (dotted ones connecting solid circles) were obtained, as shown in fig. 2 (B). In this case, the impression of the electrical phosphene produced was that of a faint flash just identical with that observed usually in cases of time-constants shorter than 25 msec., notwithstanding that the time-constant used was actually longer than 75 msec. Such two values of the high and low thresholds had been reported already in the previous paper (5), but they were not so easily demonstrable as in the case of the eye adapted

to monochromatic light of 669 m μ .

It is interesting to notice that two different values of the electric threshold correspond to two different impressions of the electrical phosphene, and that these facts can be confirmed most clearly in the case of illumination with such an extreme red ray as 669 m μ .

2) *Dependence of V_f -log N curve upon wavelength of the adapting light*

As mentioned above, the form of the V_f -log N curve is quite different according to whether the time-constant of the stimulating current is shorter than 25 msec. or longer than 75 msec. Therefore, both cases of time-constants at 0 and 100 msec. were specified as typical instances for systematic studies on the effect of wavelength of the adapting light on the V_f -log N curve. Two series of the curves obtained by varying wavelengths in both cases of time-constants at 0 and 100 msec. were illustrated in fig. 3 (A) and (B) respectively; in the interest of a clear understanding of the graphical representation, each of these curves was illustrated by shifting vertically by a certain distance.

FIG. 3. Electric threshold strength-log-radiance relation. Numbers on the curves are wavelengths of the adapting light. D : dark. Each curves is shifted vertically for graphical representation. (A) and (B) are two families of the curves obtained by stimulation with time-constant at 0 and 100 msec. respectively.

Fig. 3 (A) shows that the value of radiance (abscissa) corresponding to the crest (maximum) on the curve varies depending upon the wavelength, and that it takes a minimum at about $500\text{ m}\mu$ and increases toward both red and violet ends of the spectrum. Fig. 3 (B) shows similarly to fig. 3 (A) that the value of radiance corresponding to the beginning (or left edge) of the "horizontal section" varies depending upon the wavelength of the adapting light, and that it takes the lowest at about $500\text{ m}\mu$.

It is worth noticing that both of crest and the left edge of the "horizontal section" on the respective curves lie in the same point of abscissa (radiance) correspondingly to each other.

We can obtain a spectral sensitivity curve by taking the reciprocal of the radiance corresponding to the crest of the hump (or the left edge of the "horizontal section"), as the criterion. Fig. 4 shows that the data (filled circles) prove themselves to be consistent fairly well with the data of scotopic luminosity from Weaver (7). This finding indicates that luminosity at scotopic vision has a close relation to the formation of the crest on the $V_f\text{-log } N$ curve.

As for characteristic of the sensation produced by the adapting light, no hue could be elicited within any range of radiance corresponding to the ascending arm of the hump on the curve in fig. 3 (A) or to the "left slope" of the curve in fig. 3 (B). Hue appeared first at a radiance corresponding to the descending part toward the minimum of $V_f\text{-log } N$ curve in fig. 3 (A), and the increase in saturation of colour takes place progressively with increase in radiance.

After all, it seems likely that each of the "left slope" and the ascending arm of the hump in the respective curves relates exclusively to rod function, while each of the "horizontal section" and the descending arm of the hump in respective curves relates to concurrent participation of both cones and rods, and that the "right slope" and the ascending part transgressing the minimum may be concerned predominantly with cone function.

DISCUSSION

Sato, Suzuki and Akihama (5) studied the accommodation of the human retina to exponentially increasing currents at various intensity levels of white adapting light. They found that there were two different types of the electric

FIG. 4. Comparison of our data with Weaver's scotopic luminosity curve. Filled circles are plotted by taking reciprocal of the radiance corresponding to the crest on the curves in fig. 3 (A). The curve connecting empty circles is the scotopic luminosity curve after Weaver.

threshold strength-log-illumination curves according to whether the time-constant of the stimulating current was shorter than 25 msec. or longer than 75 msec.

At almost the same time, Mita, Fujimaki and Yaegashi (2) obtained the same conclusion from the experiments performed with use of the sinusoidal alternating currents of very low frequency as the stimuli. From this conclusion they inferred that the difference between two types of the strength-log-illumination curves for both longer and shorter time-constants might be due primarily to different seats of excitation. They, furthermore, assumed that the structures stimulated by the current of longer time-constant might be the photoreceptor cells (primary neurons), while those stimulated by the current of shorter time-constant might be the bipolar cells (secondary neurons).

As stated above, the present experiments corroborate the previous worker's findings in the main, namely, two familiar types of the strength-log-radiance curves were again demonstrated in all cases of adapting lights of different wavelengths excepting the extreme red end of the spectrum. However, it is worth noting the exceptional cases of red adapting light. All curves in fig. 3 (A) resemble in shape each other, whereas the most upper curve in fig. 3 (B) differs in shape from all the other curves in the same figure. Namely, in a special condition of experiment, where the time-constant of the stimulating current is 100 msec. and the adapting light consists of pure red rays of 669 m μ in dominant wavelength, the electric threshold strength-log-radiance curve takes a singular form which can never be found in the case of white adapting light. In this case the red rays bring about the specific effect due to the preponderance of cone function, so that the single curve for the red rays exhibits the lack of the effect due to rod function. This fact indicates that the electric threshold in this experimental condition is determined independent of rod activities, if any, but dependent solely of cone activities.

In the case of 0 msec. in time-constant, however, the circumstance is quite different from the former case; strange to say the red rays have not such a specific effect, as has been found in the case of time-constant of 100 msec. As shown in fig. 3 (A), the form of the curve for 669 m μ is of duplex nature and in common with those of the other curves for different wavelengths. This fact indicates that the electric threshold for time-constant of 0 msec. depends always not only upon rod- but also on cone-activities, irrespective of the wavelength of adapting light. After all, this difference in the effect of one and the same red rays upon the electric threshold in both cases of longer and shorter time-constants seems to be an evidence for supporting the view of different seats of excitation.

As the electric threshold means the intensity of the electric stimulus, which elicits the slightest light sensation just discriminative from brightness of the surrounding background (adapting light), it is regarded to have some relations to the differential threshold of brightness discrimination. If the electric threshold strength (V) is assumed to be proportional to logarithm of the differential threshold (ΔI), that is, the least perceptible brightness increment to be added to the brightness (I) of the background, then

$$V = K \log(\Delta I), \quad (1)$$

where K is a proportionality constant. Denoting Weber's fraction by W ,

$$\log W = \log(\Delta I/I). \quad (2)$$

From (1) and (2),

$$V = K \log(\Delta I) = K(\log W + \log I). \quad (3)$$

It is widely known that, as $\log I$ increases, Weber's fraction (W) decreases steadily and approaches a finite limiting value depending upon the size of the test-field. Some of the latest measurements of W were made by Steinhardt (6) and Blackwell (1). Their data for larger test-field exhibit a break in the curve in the section where W decreases rapidly. Using their data of $\log W$ and $\log I$, we can calculate the values of V by the formula (3). Thus, if plotted, we obtained a new V - $\log I$ curve by calculation. When the calculated V - $\log I$ curve was compared with V_f - $\log N$ curves obtained in this experiment, the former curve agreed in shape fairly well with those curves obtained in the cases of longer time-constants longer than 75 msec., whereas it did not agree with those curves obtained in the cases of time-constants shorter than 25 msec. The disagreement in the latter cases seems to occur mainly in the descending arm of V_f - $\log N$ curve; this part of the curve corresponds to the range of radiance where both rods and cones are active at the same time.

From the above mentioned facts, it may be concluded that the electric threshold determined by the exponentially increasing current of the time-constants longer than 75 msec. is equivalent to the differential threshold of brightness discrimination, while that determined by the current of time-constants shorter than 25 msec. is not. This conclusion also seems to give some credit to Mita *et al.*'s view of different seats of excitation.

SUMMARY

Taking, as a criterion, the electrical phosphene evoked by electrostimulation of the human eye with use of the exponentially increasing currents of varying time-constant (RC), a study was made on the relation between the electric threshold (V_f) of the eye and the radiance (N) of monochromatic rays of different wavelengths used as the adapting light.

(1) In any cases of adapting light of different wavelengths excepting the red light, there were two different types of V_f - $\log N$ curve depending upon whether the time-constant was shorter than 25 msec. or longer than 75 msec. This result was the same as that obtained with the white adapting light.

(2) In the case of time-constant longer than 75 msec., the effect of the red adapting light upon V_f - $\log N$ curve was quite different from that of the other adapting light; the curve showed a form of single nature, whereas in the case of time-constant shorter than 25 msec. the same red light had not such specific effect as in the former case.

(3) Taking, as a criterion, the reciprocal of the radiance corresponding to the crest on V_f - $\log N$ curve for 0 msec in RC (or the left edge of the horizontal

part on the curve for 100 msec. in *RC*), a spectral sensitivity curve was obtained. This curve was proved to be in conformity with scotopic luminosity curve.

(4) It was concluded that the electric threshold, as determined by the exponentially increasing current of time-constant longer than 75 msec. was equivalent to the differential threshold of brightness discrimination.

(5) The experiments supported Mita's view that there might be in the retina, at least near the threshold excitation, two sorts of the neural elements which were stimulated separately depending upon the time-constant of the stimulating current. The one for longer time-constant may be the photoreceptor cells, while the other for time-constant the bipolar cells.

ACKNOWLEDGEMENT

The author wishes to express his deep gratitude to Prof. T. Mita for his constant guidance and valuable advice, and to Dr. A. Akihama for his assistance given to this study.

REFERENCES

1. BLACKWELL, H. R. *J. Opt. Soc. Amer.* 36: 624, 1946.
2. MITA, T., E. FUJIMAKI AND S. YAEGASHI. *Tohoku J. Exp. Med.* 65: 45, 1956.
3. MOTOKAWA, K. AND K. IWAMA. *Tohoku J. Exp. Med.* 50: 25, 1949.
4. MOTOKAWA, K. *Tohoku J. Exp. Med.* 54: 385, 1951.
5. SATO, M., T. SUZUKI AND A. AKIHAMA. *Jap. J. Physiol.* 7: 29, 1957.
6. STEINHARDT, J. *J. Gen. Physiol.* 20: 185, 1936.
7. WEAVER, K. S. *J. Opt. Soc. Amer.* 39: 278, 1949.
8. YAEGASHI, S. *Tohoku J. Exp. Med.* 67: 163, 1958.