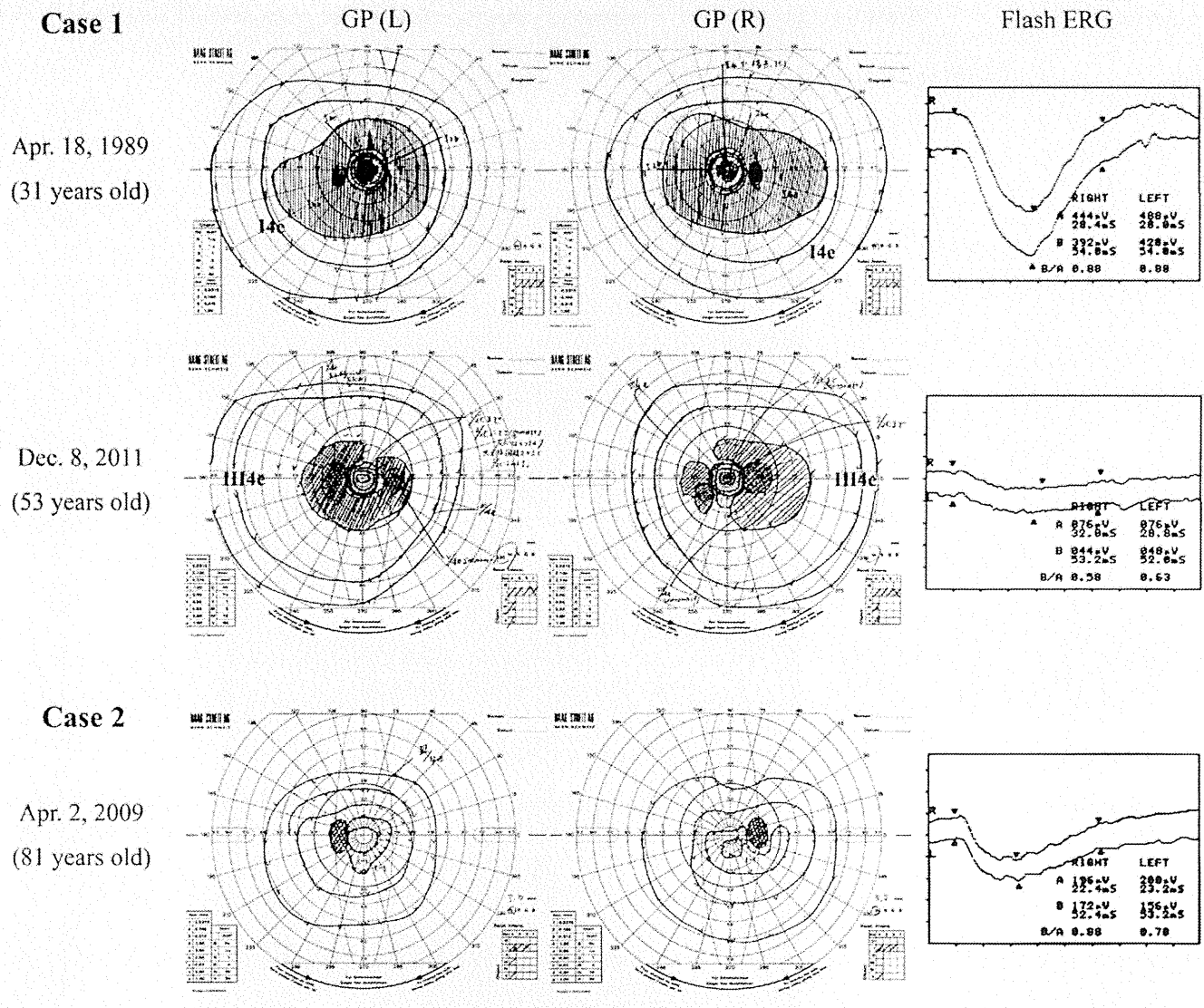

Figure 3. Results of Goldmann perimetry (GP) and flash electroretinography (ERG). In case 1, retinal sensitivity decreased and amplitude of ERG was attenuated during the 2-decade follow-up. In case 2, the visual field and the ERG findings were maintained relatively well in spite of her great age. This Figure was made with modification of Figures 2, 3, and 8 in Sato et al[3] with permission.

Figure 2. Results of fundus photography, fluorescein fundus angiography (FA) and optical coherence tomography (OCT) in case 1. At the initial visit (April 1989), cystic changes were observed in the fovea that became ambiguous 2 decades later; vision, however, did not improve. This figure was made with modification of Figures 1 and 6 in Sato et al,[3] with permission.

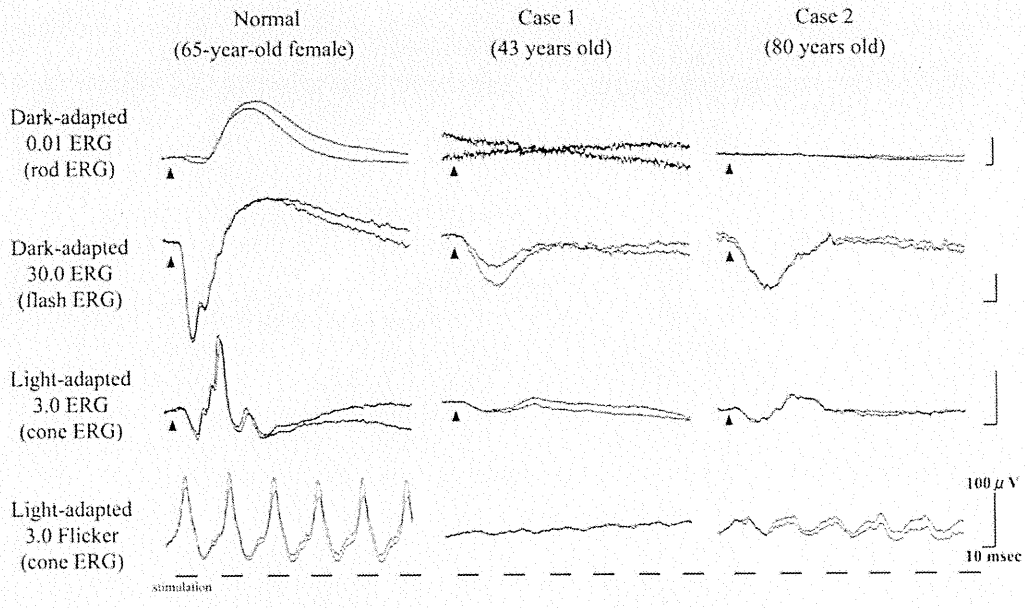

Figure 4. International Society for Clinical Electrophysiology of Vision (ISCEV)-standard electroretinography (ERGs) images. The 2 cases showed nonrecordable rod responses and significantly prolonged flash ERGs. Flicker ERGs derived from the middle- and long-wavelength-sensitive (M- and L-) cone systems were attenuated in these cases. These findings were consistent with enhanced S-cone syndrome. This figure was made with modification of Figure 4 in Sato et al[3] with permission.

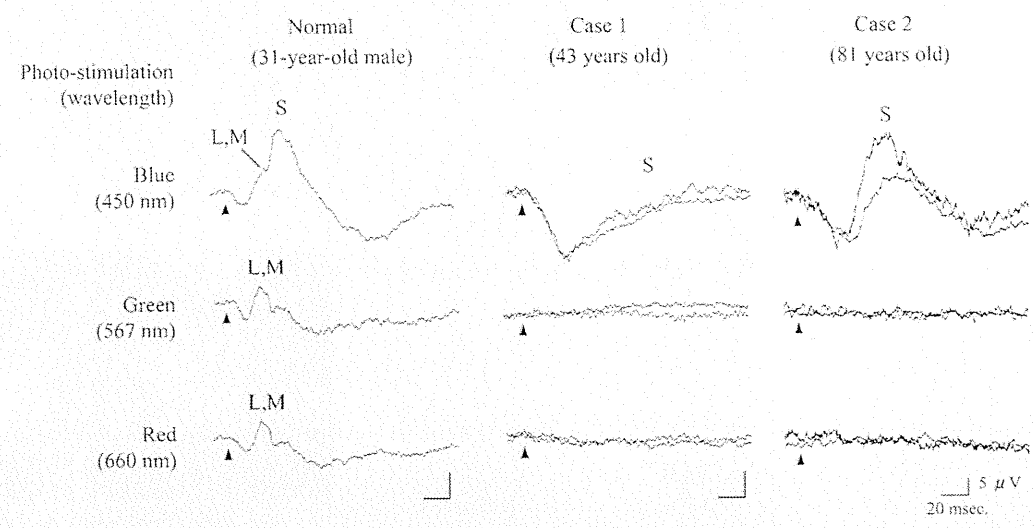

Figure 5. Color electroretinography (ERGs) images. The ERGs were recorded using 3-colored LED-built-in electrode (Kuniyoshi et al. Doc Ophthalmol 2003;106:311-8). The ERGs were elicited by 3 kinds of stimulus, namely, blue, green, and red light under the yellow background light. Luminance of the yellow background light was 670 cd/m^2 and duration of the stimulus was 2 milliseconds. The ERG waveform elicited by blue stimulus in the normal subject showed double-peaked, namely, rapid b-wave, which was derived from the L- and M-cone systems (L, M) followed by slow b-wave derived from the S-cone system (S). In cases 1 and 2, large b-wave with slow peak time was recorded with blue photostimulation, whereas no response was recorded with green and red photo stimuli. The intensity of the color stimulus was decided to elicit the rapid b-wave (L, M) with almost the same amplitude as in the normal subject. This Figure was made with modification of Figure 5 in Sato et al[3] with permission.

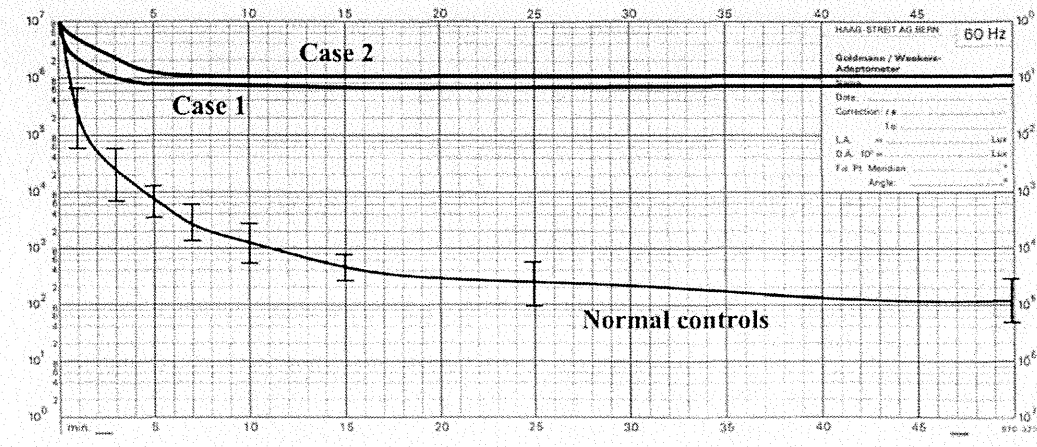

Figure 6. Results of Goldmann-Weekers dark adaptometry. Lower line indicates averaged value and its standard deviation resulted from normal controls.

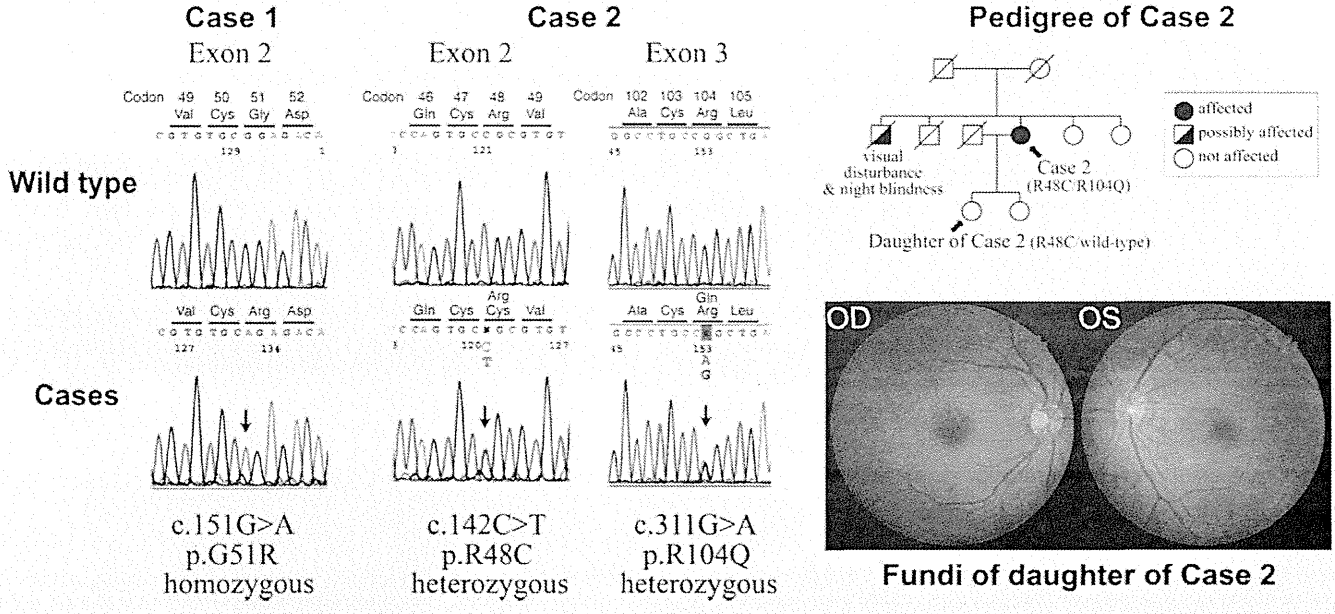

Figure 7. Results of DNA sequencing of the *NR2E3* gene in cases 1 and 2 (left), the pedigree of case 2, and fundus photographs of the daughter of case 2 (right). Mutation analysis identified a novel homozygous missense mutation of p.G51R, which resides in the DNA-binding domain (DBD) in NR2E3 protein in case 1. In case 2, heterozygous missense mutation of p.R48C and p.R104Q were identified, and the former is a novel mutation. A daughter of case 2 revealed heterozygous missense mutation of p.R48C and normal fundus appearance. In mutation screening of the *NR2E3* gene, all coding exons including exon/intron boundaries were amplified using polymerase-chain reaction (PCR) with primer pairs followed by sequencing. The primers and protocols used for PCR, and the procedures of PCR amplification and purification were the same as reported previously.[3]

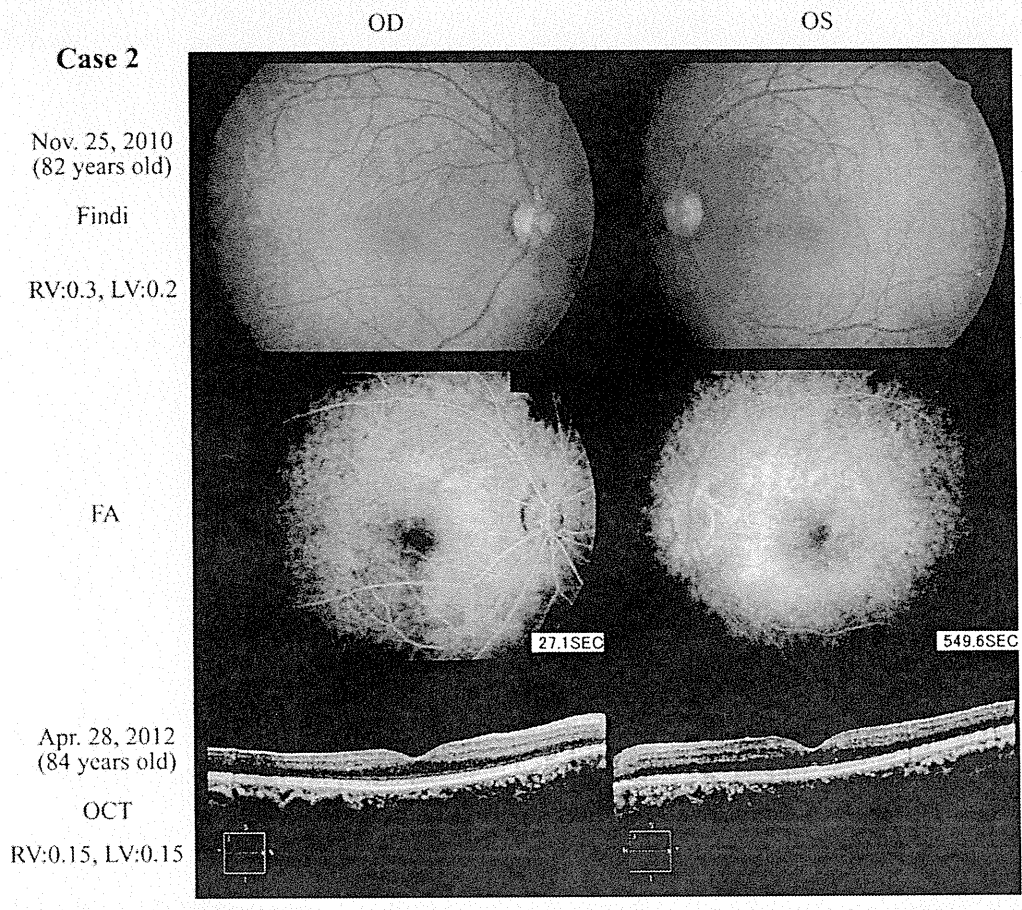

Figure 8. Results of fundus photography, fundus angiography (FA), and optical coherence tomography (OCT) in case 2. These photographs were taken after cataract surgery. The retinal degeneration was relatively mild with no pigmentation in both eyes. This Figure was made with modification of Figure 7 in Sato et al[3] with permission.

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CLINICAL CASE REPORT

A case of bilateral, acquired, and acute dysfunction of short-wavelength-sensitive cone systems

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Abstract To report a case of bilateral, acquired, and acute dysfunction of short-wavelength-sensitive (SWS) cone systems. The case was a healthy 39-year-old man. He noticed sudden onset of bilateral abnormal color vision. Ophthalmic examinations revealed normal fundi in both eyes. Farnsworth panel D-15 test and Farnsworth–Munsell 100-hue test showed tritanopia. White-on-white static perimetry showed no abnormality; however, blue-on-yellow static perimetry detected remarkably reduced sensitivity at the lower visual field in both eyes. ISCEV-standard full-field electroretinograms (ERGs) were normal; however, blue-on-yellow ERGs showed reduced amplitude of b-wave that was derived from SWS cone systems in both eyes. He was observed for 1 year, and no improvement in color vision was found during the observation. This is a unique case which showed bilateral, acquired, and acute dysfunction of SWS cone systems. The cause of the acquired tritanopia remains to be known.

Keywords Acquired tritanopia · Color blindness · Electroretinogram · Short-wavelength-sensitive cone · Blue-on-yellow perimetry

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Introduction

Acquired tritanopia is shown in various retinal diseases and optic nerve diseases [1], or after exposure to toxic chemicals [2].

In this paper, authors report a case with bilateral, acquired, and acute dysfunction of short-wavelength-sensitive (SWS) cone systems which had no history of general or ophthalmic diseases.

Case

The case was a healthy 39-year-old man. He had no past history of general disease or medication. He was working as an office worker. He noticed abnormal color vision in both eyes when he woke up on the morning of June 2, 2009. He complained that yellow color looked whitish, human skin of Asian looked vivid pink, and it was difficult to distinguish between blue and green. He had not been exposed to strong light nor chemical materials such as organic solvents that were reported as cause of acquired color discrimination impairment. He did not take much alcoholic drinks before the symptoms, nor tobacco, except several electronic cigarettes. He visited a nearby clinic and was referred to us for further examinations.

At the first visit to our clinic, the corrected visual acuity was (1.2) in both eyes with normal intraocular pressure. Ophthalmic examinations revealed that the anterior segments, optic media, and fundi were

unremarkable in both eyes (Fig. 1). Fluorescein fundus angiography, indocyanine-green fundus angiography, and optical coherence tomography were performed, and they were also unremarkable (Figs. 2, 3). Farnsworth panel D-15 test and Farnsworth–Munsell 100-hue test showed tritanopia in both eyes (Fig. 4). Goldmann kinetic perimetry and white-on-white static perimetry showed no abnormality in either

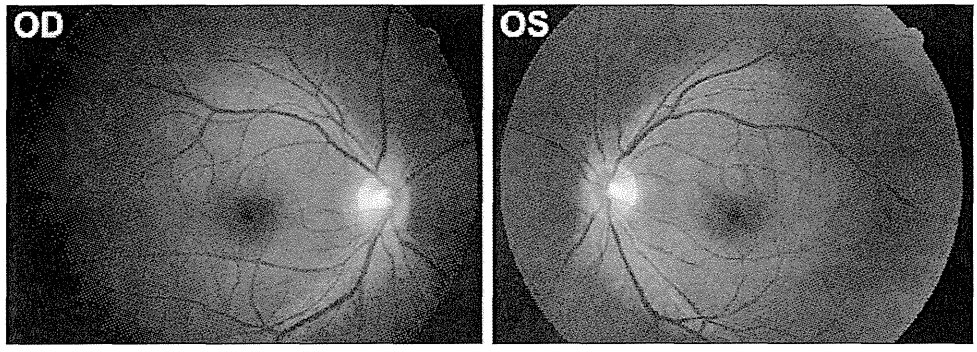

Fig. 1 Fundus photographs. No abnormality was found in both eyes

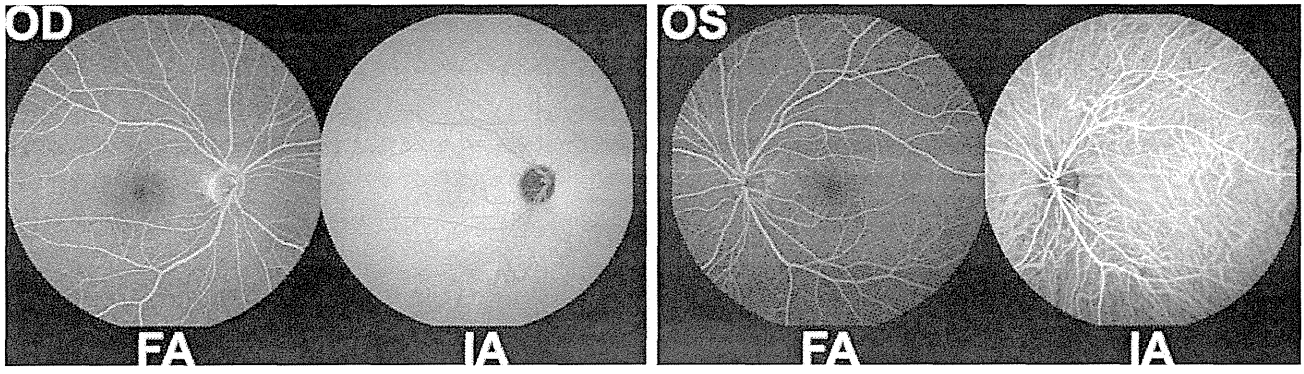

Fig. 2 Results of fluorescein and indocyanine-green fundus angiograms (FA and IA). FA and IA were performed simultaneously using HRA^{TM}2 (Heidelberg Engineering, Heidelberg, Germany)

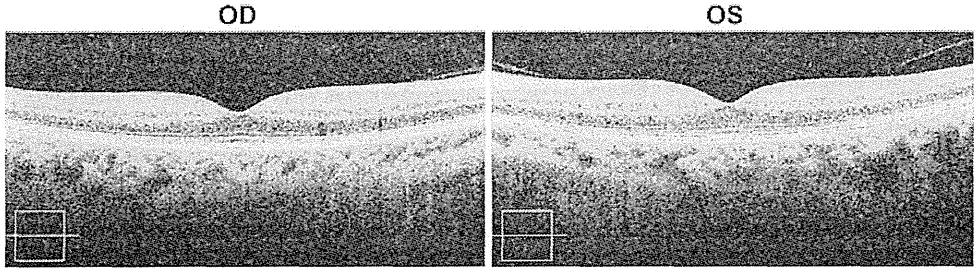

Fig. 3 Results of optical coherence tomography (OCT). Horizontal section of macular area was shown. Retinal structure was normal including photoreceptor layer, middle layer, and nerve fiber layer. OCT was performed using Cirrus^{TM} HD spectral-domain optical coherence tomography (Cirrus^{TM} HD-OCT; Carl Zeiss Meditec, Dublin, CA)

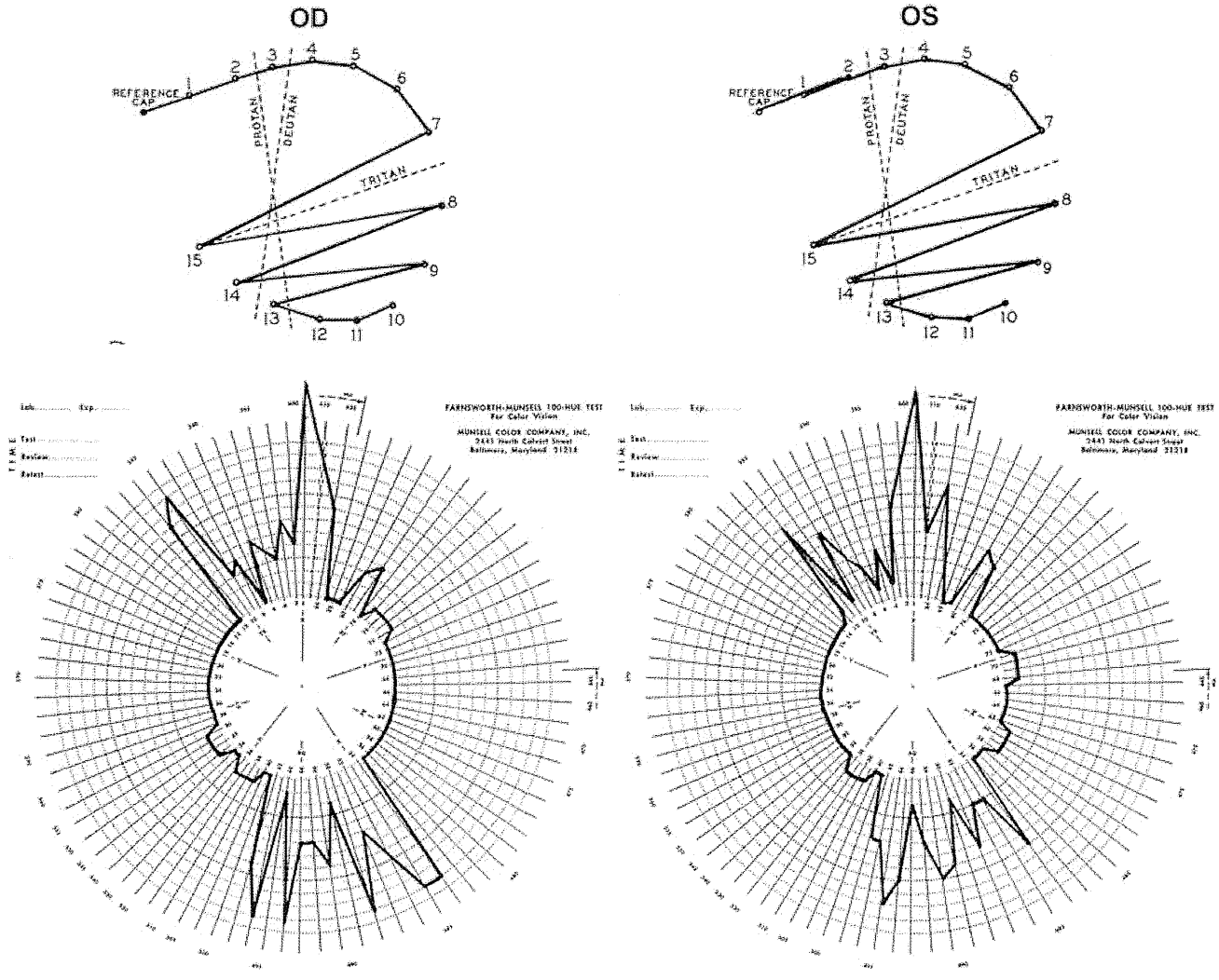

Fig. 4 Results of Farnsworth panel D-15 test (*upper row*) and Farnsworth–Munsell 100-hue test (*lower row*). Tritanopia is suggested clearly in both eyes

eye; however, blue-on-yellow static perimetry detected remarkably reduced sensitivity at the lower visual field in both eyes (Fig. 5).

ISCEV-standard full-field electroretinograms (ERGs) [3] were normal (Fig. 6); however, blue-on-yellow ERGs [4] showed attenuated b-wave that was derived from SWS cone systems in both eyes (Fig. 7).

Optic nerve and central nervous system were investigated using magnetic resonance imaging and recording of visual evoked potentials, and they were unremarkable.

The patient quitted smoking the electronic cigarette after the symptom, and he was observed for 1 year. However, his condition was stationary with no improvement or worsening of color vision, visual acuity, and fundus appearance.

Discussion

The SWS cone system is vulnerable in retinal diseases compared to middle- and long-wavelength-sensitive (MWS and LWS) cone systems [5–8].

The results of color vision test indicated distinct tritanopia (Fig. 4). And the reduction in SWS-cone ERG (Fig. 7) indicated that the tritanopia was caused

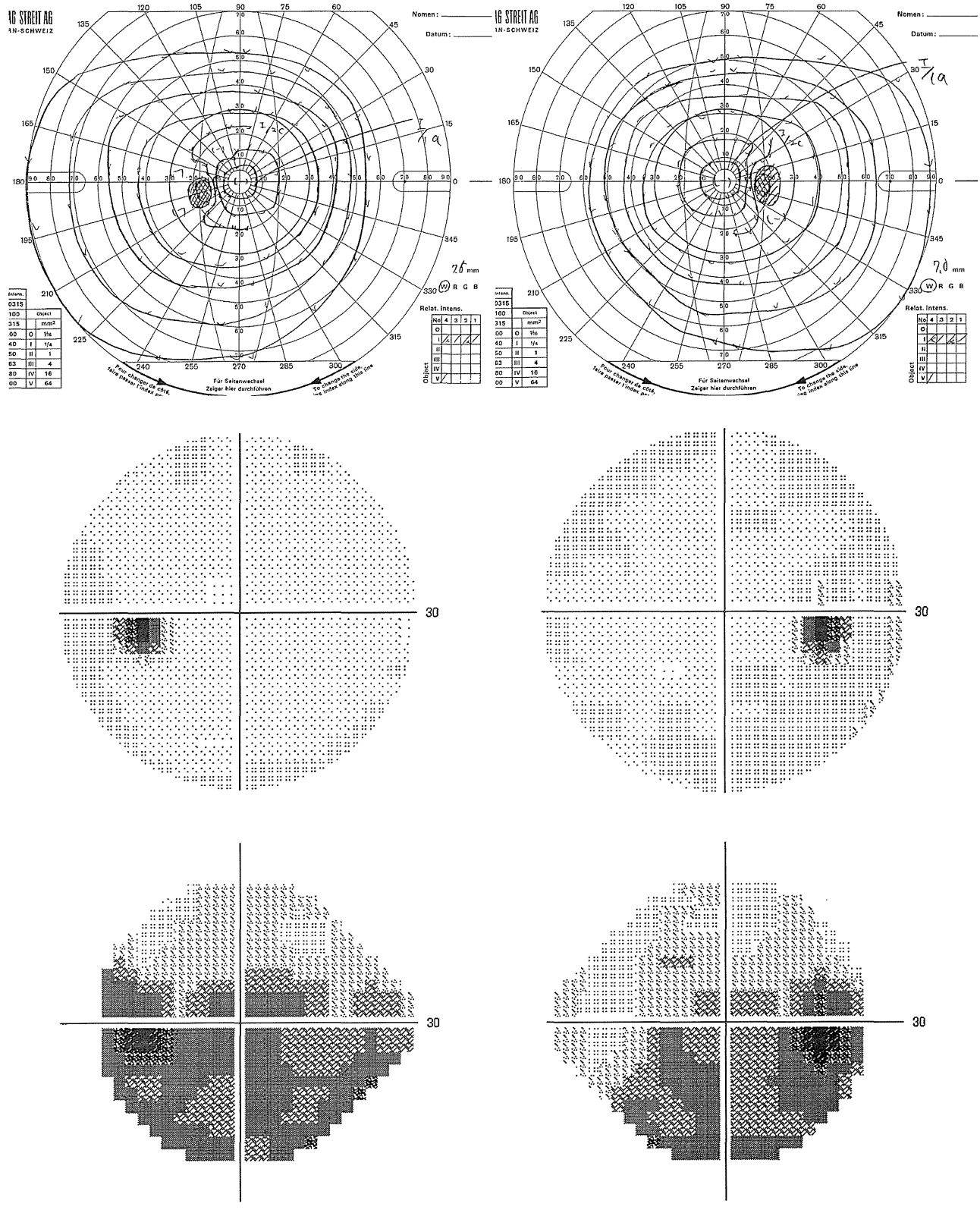

Fig. 5 Results of Goldmann kinetic perimetry (GP *upper row*), Humphrey white-on-white static perimetry (W/W *middle row*), and Humphrey blue-on-yellow static perimetry (B/Y *lower row*). No visual field defects were detected except in blue-on-yellow static perimetry

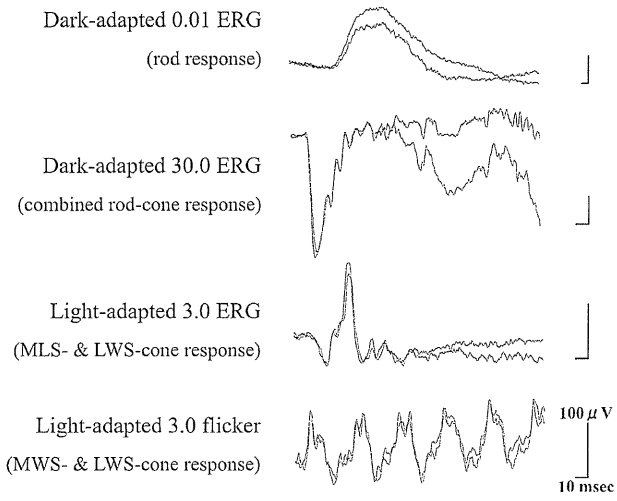

Fig. 6 ISCEV-standard ERGs [3]. Responses from both eyes were superimposed. Photopic and flicker ERG that were derived from middle- and long-wavelength-sensitive (MWS and LWS) cone systems showed normal responses

by dysfunction of SWS cone systems in the retina, in spite of the fact that the fundus appearance was normal. LWS and MWS cone systems seemed to be healthy in this case, because Farnsworth–Munsell 100-hue test showed very few errors in red-green color vision, and full-field photopic and flicker ERG that were derived from MWS and LWS cone systems showed normal responses (Figs. 4, 6). These facts suggest a selective functional disturbance of SWS cone systems in this case.

The patient reported that he had used electronic cigarettes several days before the symptom. Although World Health Organization (WHO) has denied safety of the electronic cigarette [9], relationship between the electronic cigarette and the SWS cone dysfunction was not clear in this case, because authors did not examine the electronic cigarettes he took.

To our knowledge, acquired tritanopia and acute tritanopia due to SWS cone system dysfunction with no ophthalmic diseases have never been reported except by Okuno et al. [10]. They reported a case of sudden-onset tritanopia with no ophthalmic nor general disease. The color vision abnormality in the Okuno's case [10] was unilateral, which is different from our case.

Bilateral and acute dysfunction of SWS cone systems in the case presented here is quite unique. Authors were not able to find any causes of this dysfunction during the 1-year follow-up.

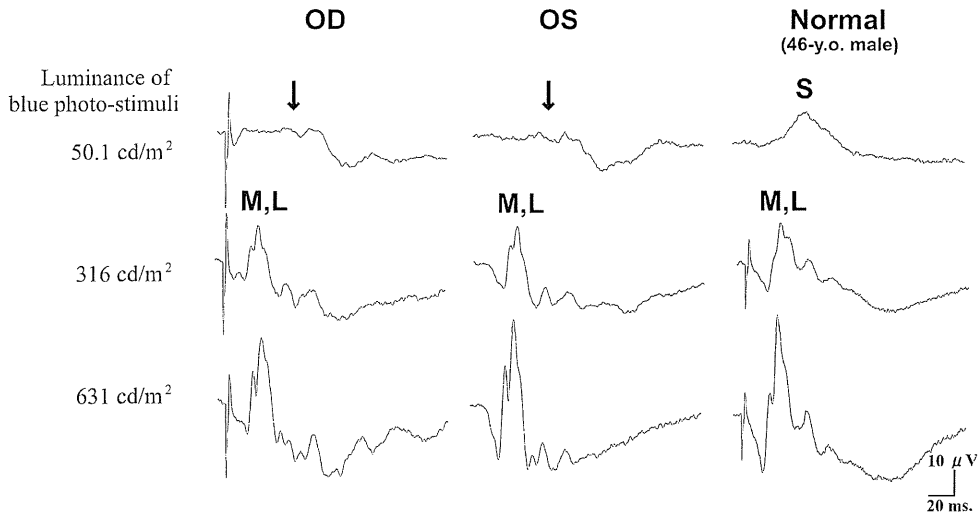

Fig. 7 Blue-on-yellow ERGs [4]. The case showed severely attenuated b-wave (*arrows*) that was derived from short-wavelength-sensitive cones in a normal subject (S), whereas b-waves from middle- and long-wavelength-sensitive cones (M, L) were normal in both eyes. Luminance of the yellow background was 640 cd/m^2, and duration of the blue photo-stimuli was 2 ms

Conflict of interest The authors declared that there is no conflict of interest.

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Review Article

Clinical Applications of the Photopic Negative Response to Optic Nerve and Retinal Diseases

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The photopic negative response (PhNR) in response to a brief flash is a negative-going wave following the b-wave of the cone electroretinogram (ERG) that is driven by retinal ganglion cells (RGCs). The function of RGCs is objectively evaluated by analysing the PhNR. We reviewed articles regarding clinical use of the PhNR. The PhNR was well correlated with the visual sensitivity obtained by standard automated perimetry and morphometric parameters of the inner retina and optic nerve head in optic nerve and retinal diseases. Moreover, combining the PhNR with focal or multifocal ERG techniques enables the objective assessment of local function of RGCs. The PhNR is therefore likely to become established as an objective functional test for optic nerve and retinal diseases involving RGC injury.

1. Introduction

Retinal ganglion cells (RGCs) are selectively or preferentially damaged by diseases of the optic nerve and inner retina. Currently, there are surprisingly few methods to quantify RGC function. Visual field testing is used to determine visual function in patients with glaucoma and optic nerve disease, but it produces abnormal findings in the event of damage anywhere along the anterior visual pathway. Accordingly, this test method is not necessarily capable of selectively determining RGC function.

Objective tests of RGC function include visual evoked potentials (VEPs) and pattern electroretinograms (PERGs). The VEP measures potentials generated by the visual cortex, so, like visual field testing, it cannot directly measure RGC function. The PERG, on the other hand, reflects RGC function but still yields abnormal findings in patients with damage to the middle and outer layers of the retina. Standard ERGs must be recorded simultaneously in order to evaluate the function of the middle and outer retinal layers. Moreover, special equipment and refractive correction are required to perform this electrophysiological test.

The standard ERG is conventionally thought to reflect electrical potentials mainly from photoreceptors and bipolar cells (or Müller cells). Recently, however, it was discovered that the RGC potentials contribute to the cone-driven ERG [1] in the form of the photopic negative response (PhNR) [2]. The PhNR in response to brief stimuli is the negative-going wave following the b-wave of the cone response (Figure 1). An advantage of the PhNR is that it can be recorded using a conventional ERG recording device. Furthermore, the PhNR is a component of the cone ERG, so a- and b-waves can be recorded simultaneously enabling the function of middle and outer retinal layers to be evaluated at the same time. This benefit is not available when assessing RGC function with the conventional means of the VEP or PERG. In addition, refractive corrections are not required when recording the PhNR. This simple recording and evaluation of the PhNR opens the way for clinical applications. The present paper therefore describes the potential clinical use of the PhNR in diseases of the optic nerve and inner retina.

2. Basic Research on the PhNR

2.1. Discovery of PhNR in Monkeys. RGC component in the cone ERG was discovered by Viswanathan et al. in 1999 [2]. They reported that the PhNR following the b-wave of the

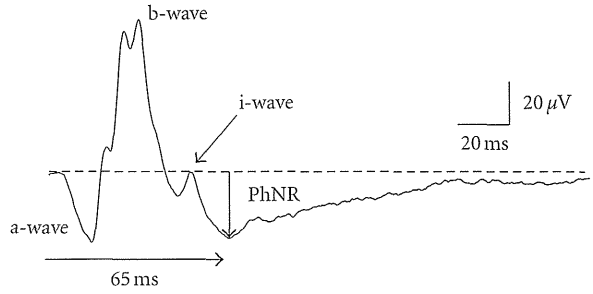

FIGURE 1: A representative waveform of the cone electroretinogram recoded from a normal subject by red stimuli on a blue background. PhNR: photopic negative response.

cone ERG disappeared from eyes of macaques after intravitreal injection of tetrodotoxin (TTX) which blocks voltage-gated sodium channels and thus blocks action potentials produced by RGCs and spiking amacrine cells [3, 4]. They also demonstrated that PhNR amplitudes were decreased in glaucomatous eyes with laser-induced ocular hypertension in monkeys. These experimental results implied that the PhNR arises from RGCs and/or their axons. However, one may have question why spiking action potentials produced by RGCs shape a slow negative waveform. Experimental evidence suggests that glial mediation generates the PhNR: an intravitreal injection of Ba^{2+} blocks K^{+} current in glia cells with the subsequent elimination of the PhNR in cats [5]. This suggests that glial mediation could contribute to shaping waveform of the PhNR.

Caution is needed when attempting to determine the origin of the PhNR because of its species specificity. In cat [6], monkeys [2], and humans [7] it derives from RGCs, but in animals such as rodents it originates from amacrine cells [8, 9]. The scotopic threshold response (STR) [10] which is elicited by very dim light under dark adaptation is a functional indicator of RGCs in rodents [8]. In rodents, the STR consists of positive and negative components. The positive STR is more affected by RGC damage than the negative STR [8].

2.2. PhNR Recording Conditions. The International Society for Clinical Electrophysiology of Vision (ISCEV) recommends that cone ERGs be recorded using white-flash stimuli on a white background light ("white-on-white"; W/W) [11]. On the other hand, Viswanathan et al. [2], who published the first study on the PhNR, used red-flash stimuli on a blue background ("red-on-blue"; R/B) to record the PhNR. The colored flash stimuli and background are generated by light-emitting diodes (LEDs), giving them a narrow, half-width spectrum. It has been shown that R/B elicited the PhNR with more RGC responses than did W/W especially in the low and intermediate stimulus range [12]. While future studies are needed to determine the ideal stimulus conditions for evaluating PhNR, RGC-derived potentials are reflected in the PhNR recorded under either W/W or R/B conditions.

The S-cone ERG can be recorded by blue stimuli under a yellow background to suppress responses of the M- and L-cones. The PhNR of the S-cone ERG is reported to be especially vulnerable to glaucoma and diabetic retinopathy [13, 14].

2.3. PhNR in Focal ERG (Focal PhNR). The focal ERG developed by Miyake et al. [15] consists of the a-wave, b-wave, oscillatory potentials, and PhNR (focal PhNR) (Figure 2). The focal ERG stimulus system is built into an infrared fundus camera and delivers stimuli onto the local retina using a 5–15° stimulus spot while viewing the ocular fundus (Figure 2(a)). This allows the device to acquire very reliable data from the macula, even in individuals with poor fixation. Colotto et al. [16] firstly applied the focal PhNR to patients with glaucoma, although they used a different recording system from Miyake's one.

Like the PhNR obtained by full-field stimuli (full-field PhNR), the focal PhNR also disappeared following intravitreal injection of TTX in monkey eyes [17]. Moreover, the amplitude of both focal and full-field PhNR was reduced in patients with optic nerve atrophy [18]. Based on these results, the focal PhNR is also believed to originate from RGCs of the local retinal area.

2.4. PhNR in Multifocal ERG (Multifocal PhNR). In the standard multifocal ERG, the stimulus frequency is set high at 75 Hz. A stimulus is delivered once every 13.3 msec, making it hard to record the entire part of the PhNR, which has a peak latency of approximately 70 msec. The amplifier settings also eliminate the most part of PhNRs because the low-cut filter is usually set at 10 Hz. It is therefore essential to reduce the stimulus frequency and low-cut filter in order to record PhNRs with the multifocal ERG.

With this in mind, we attempted to record the multifocal ERG by setting the stimulus frequency at 6.25 Hz and low-cut filter at 3 Hz using a stimulus display with a dartboard pattern (Figure 3(a)). The respective patterns are inverted from white to black and vice versa in a pseudorandom sequence. Waveforms resembling focal ERG containing PhNRs were obtained from each element (Figure 3(b)). Kaneko et al. [19] have demonstrated that the multifocal PhNR amplitudes were deteriorated by optic nerve atrophy, indicating that the multifocal PhNR also originates from RGCs. While the clinical significance of the PhNR in the multifocal ERG is a topic for future research, the use of the multifocal ERG may

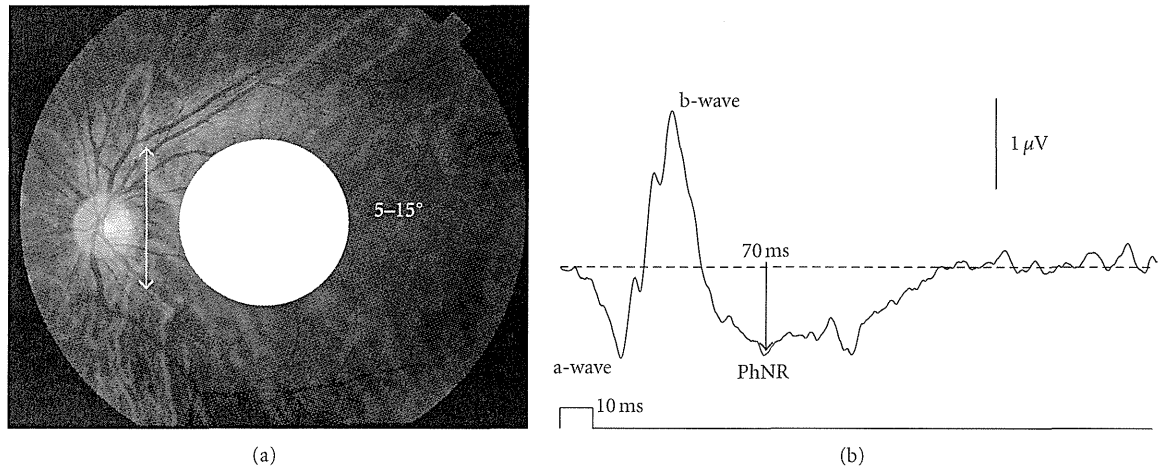

FIGURE 2: (a) Stimulus spot centered on the macula for recording the focal macular electroretinogram (ERG). (b) The focal macular ERG consists of the a- and b-waves and photopic negative response (PhNR).

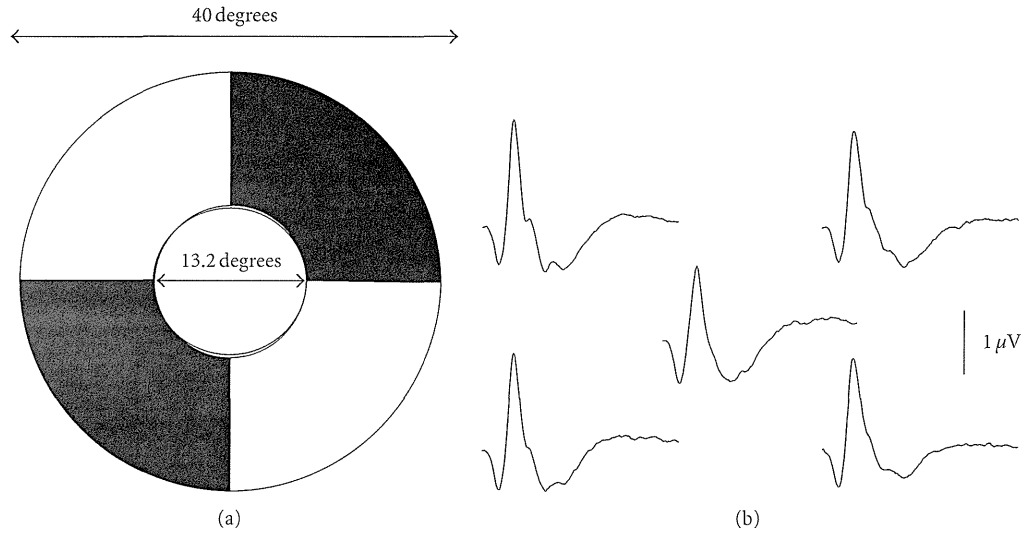

FIGURE 3: (a) A dartboard pattern of stimuli for recording the multifocal electroretinogram (ERG). (b) Normal waveforms of multifocal ERG recorded from each element.

allow us to evaluate the RGC function in each part of the retina in the posterior pole of the ocular fundus.

2.5. Evaluation of PhNR. The PhNR is a relatively slow wave modified by positive i-waves, so its peak is often difficult to determine. This in turn makes it difficult to accurately evaluate peak latency of the PhNR. Measuring PhNR amplitude in healthy individuals at 5 ms intervals yielded a maximum amplitude at 65 ms for full-field PhNR and 70 ms for focal PhNR. Full-field and focal PhNR amplitudes at 65 and 70 ms, respectively, have therefore been measured from the baseline (Figures 1 and 2(b)). However, the waveform of the PhNR changes with recording conditions, such as stimulus parameters and amplifier settings. Adequate settings of low-cut filters are required for reliable recordings of the PhNR by avoiding low-frequency drift of the baseline. Therefore, each laboratory has to choose a fixed implicit time for measuring the PhNR amplitude based on own data. This method of measuring PhNR amplitude is believed to be the simplest and least biased, but there is still no consensus on a uniform method. In fact, various studies use different measurement procedures, so care needs to be exercised in this regard.

3. Clinical Applications of PhNR

3.1. Optic Nerve Atrophy. The PhNR has been studied in patients with optic nerve atrophy induced by trauma [20], gene mutation [21], inflammation [22], compression [23, 24], and ischemia [25]. In these studies, the PhNR has been shown to be selectively or predominantly affected by these diseases. In our previous study examining changes in the cone ERG of patients with traumatic optic neuropathy,

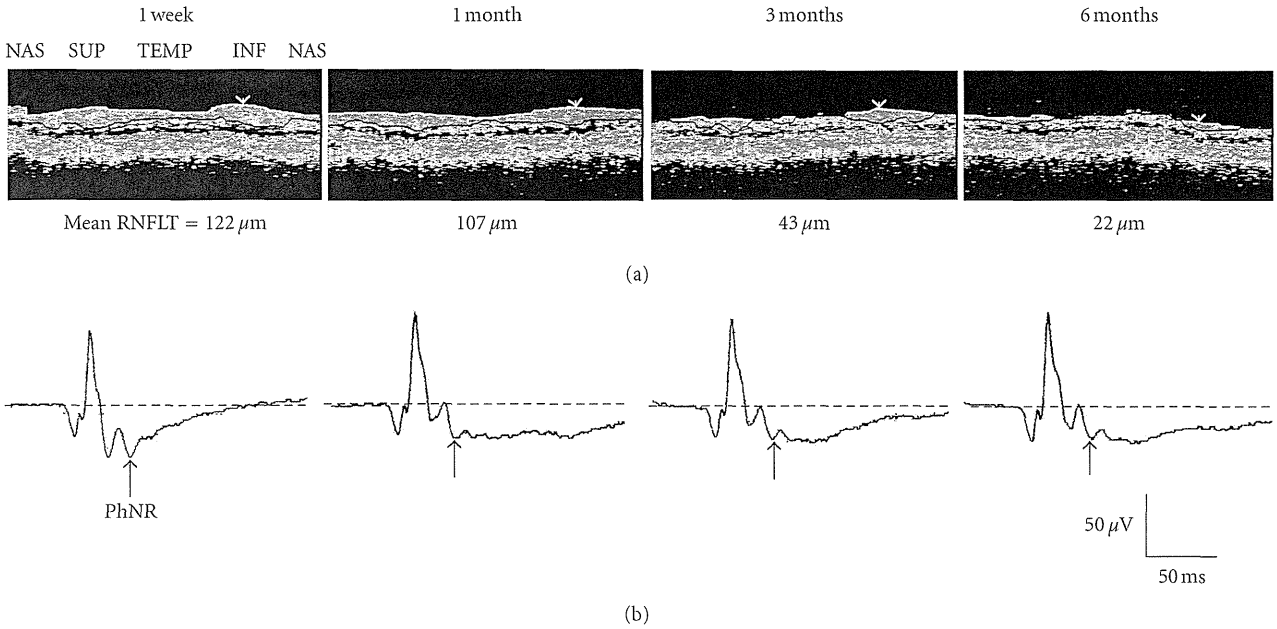

FIGURE 4: (a) Retinal nerve fiber layer thickness (RNFLT) around the optic nerve head measured by optical coherence tomography in a patient with traumatic optic neuropathy at 1 week and 1, 3, and 6 months after the injury. (b) Cone electroretinograms recorded simultaneously. PhNR: photopic negative response (reproduced with permission from [20]).

we found that ERG was virtually normal immediately after the injury but that the PhNR amplitude alone decreased selectively upon the onset of optic disc atrophy and optic nerve pallor [20]. This finding suggests that PhNRs reflect the state of RGCs and do not appear abnormal when the lesion is confined to the optic nerve behind the eye and when intraocular RGCs are normal.

We previously conducted a prospective study of the relationship between the PhNR amplitude following traumatic optic neuropathy and retinal nerve fiber layer thickness (RNFLT) surrounding the optic disc [20] (Figure 4). Even when RNFLT was maintained at 1 month after the injury, the PhNR amplitude declined dramatically. This decrease in the PhNR amplitude preceded thinning of RNFLT. In other words, RGCs undergo a functional decline before the occurrence of morphological changes.

The full-field PhNR is believed to be characteristic of overall RGC function and could therefore be used to evaluate function in optic nerve diseases with extensive RGC damage. However, many patients with optic nerve disease have central scotoma in which extensive RGC injury is not necessarily present. Therefore, if the focal ERG could be used to determine the RGC function in the local retina, this could conceivably lead to improvements in diagnostic capability.

In our previous study in which the full-field cone and focal macular ERGs were recorded in patients with localized optic nerve atrophy, we compared the full-field and focal PhNRs [18]. In a representative case, a slight pallor was observed on the temporal side of the optic disc corresponding to abnormally thinning area of ganglion cell complex (GCC) thickness in the central area of the ocular fundus (indicated by red areas), and central scotoma was also observed (Figure 5(a)). GCC consists of the retinal nerve fiber, ganglion cell, and inner plexiform layers. The full-field PhNR amplitude remained normal, but the focal PhNR amplitude diminished considerably (Figure 5(b)). This finding implies that the focal PhNR is an indicator of local RGC damage. Previously, we examined both central and diffuse types of optic nerve atrophy [18]. The central type manifests as central scotoma whereas the diffuse type is characterized by a diffuse decrease in the visual sensitivity. In patients with diffuse-type of optic nerve atrophy, both focal and full-field PhNR amplitude fell below the lower limit of normal. Meanwhile, those with the central type of optic nerve atrophy exhibited normal full-field PhNR amplitude but a decline in the focal PhNR amplitude to below the normal limit. These results imply that the focal PhNR is useful in diagnosing localized optic nerve atrophy.

3.2. Glaucoma. Glaucoma is a typical disease involving damage to RGCs. As shown in Figure 6(a) in a glaucomatous eye, the cone a- and b-wave amplitudes are normal but the PhNR amplitude of the full-field cone ERG is diminished [7, 26, 27]. This decrease in full-field PhNR amplitude grew as the glaucoma became more severe (Figure 6(b)). It was also reduced as the mean deviation determined by static automated perimetry (SAP) worsened [26, 27]. Significant correlations have been identified between full-field PhNR amplitude and the morphological indicators of RNFLT surrounding the optic disc, the optic disc rim area, and cup/disc area ratio [26, 27]. Put simply, the full-field PhNR is a feasible indicator of glaucoma-induced functional and morphological impairment of RGCs.

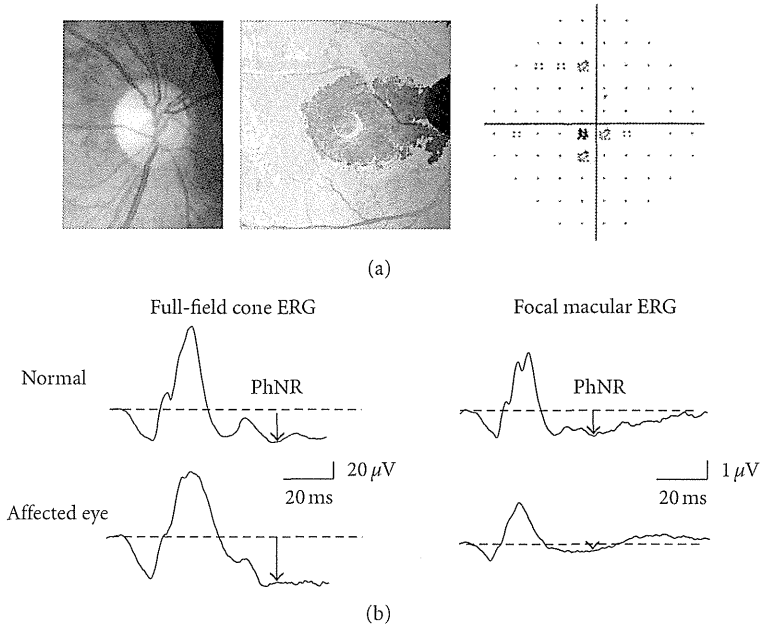

FIGURE 5: A representative case of optic nerve atrophy. (a) Optical coherence tomography detected abnormally thinning area of ganglion cell complex thickness (indicated by red area). Standard automated perimetry demonstrated central scotoma. (b) The full-field cone and focal macular electroretinograms (ERGs) recorded from a normal subject and the representative case. PhNR: photopic negative response.

The sensitivity and specificity to detect glaucoma by full-field PhNRs were 77% and 90%, respectively. However, the sensitivity declined to 57 [26] or 38% [27] for early-stage glaucoma, so the full-field PhNR was not a viable method of detecting the disease at the early stage. In early-stage glaucoma the RGC axons are locally damaged, so the full-field PhNR (which reflects the RGC function of the entire retina) is not suitable for determining localized RGC injury. On the other hand, changes in early-stage glaucoma could be detected if it were possible to record focal PhNRs from damaged RGCs using the focal ERG.

Glaucoma-induced RGC damage begins in the paramacular region (Bjerrum's area). Therefore, detection of early glaucomatous lesions would be difficult if the focal ERG was recorded only in macular region. With this in mind, we recorded the focal ERG not only in the macular region but also in the superotemporal and inferotemporal areas of the macula (Figure 7(a)) [27, 28, 31]. With this protocol, it is possible to record evaluable focal PhNRs from all stimulus sites (Figure 7(b)). As seen in the representative case of early glaucoma with a visual field defect in the inferonasal quadrant, the only decrease in the focal PhNR amplitude was seen in the superotemporal retina corresponding to the visual field defect (indicated by an asterisk, Figure 8(a)). Thus, the focal PhNR amplitude only decreased in 1 or 2 of the 3 recording sites in patients with early or intermediate glaucoma. When the focal PhNR amplitude was abnormally reduced in either recording sites, the eyes were defined to be glaucomatous. Consequently, sensitivity and specificity were no less than 90% even for early glaucoma when this diagnostic criterion was employed. In advanced glaucoma with severe visual field defects, the focal PhNR amplitude decreased at all recording sites (indicated by asterisks, Figure 8(b)).

The high sensitivity of the focal PhNR indicates that the focal PhNR is more suitable than the full-field PhNR for detecting functional loss of early glaucoma. However, the signal of the ERG is much smaller than that of the full-field ERG and thus the signal/noise ratio is smaller for the focal ERG, raising a possibility that the focal PhNR is less reliable than the full-field PhNR. Intersession variability is represented by the coefficients of variation (CV = standard deviation/mean × 100), and it was higher for the focal PhNR than for the full-field PhNR [26, 31]. In addition, variations of the PhNR amplitude among individuals were greater for the focal PhNR amplitude than for the full-field PhNR amplitude [26, 31]. However, this disadvantage of the focal PhNR can be reduced by using the amplitude ratio of the PhNR to the b-wave amplitude [31]. Therefore, the PhNR/b-wave amplitude ratio is recommended for measuring the effectiveness of the focal PhNR.

The relationship between the focal PhNR amplitude and visual sensitivity (dB) determined by SAP at either ERG recording site was nonlinear [31]. That is, even a slight drop in the visual sensitivity (dB) resulted in a major decline in the focal PhNR amplitude. Furthermore, even when the visual sensitivity (dB) fell, the focal PhNR amplitude remained nearly unchanged (Figure 9(a)). These findings suggest that the focal PhNR is a useful indicator in the early diagnosis of glaucoma. Put differently, the focal PhNR is unsuitable for use in following up patients with intermediate or advanced glaucoma, and the visual sensitivity (dB) should instead be

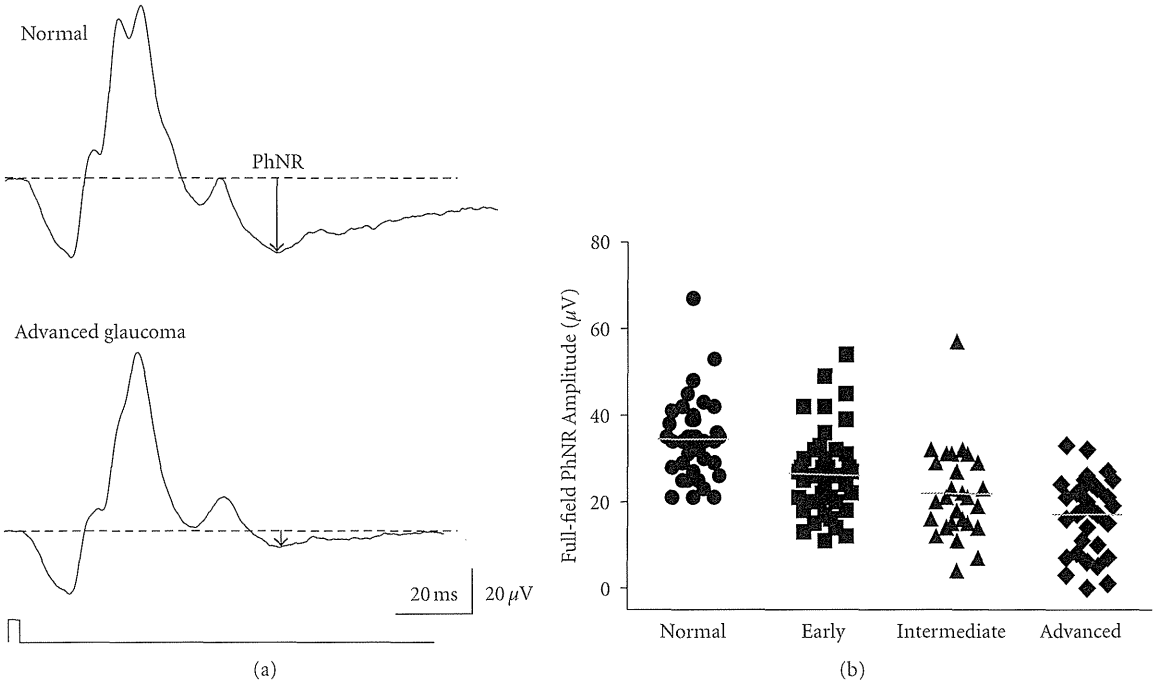

FIGURE 6: (a) Representative waveforms of the full-field cone electroretinogram recorded from a normal subject and a patient with advanced glaucoma. (b) PhNR amplitudes were plotted for normal subjects ($n = 42$) and patients with early ($n = 41$), intermediate ($n = 28$), and advanced glaucoma ($n = 34$). PhNR: photopic negative response (reproduced with permission from [27]).

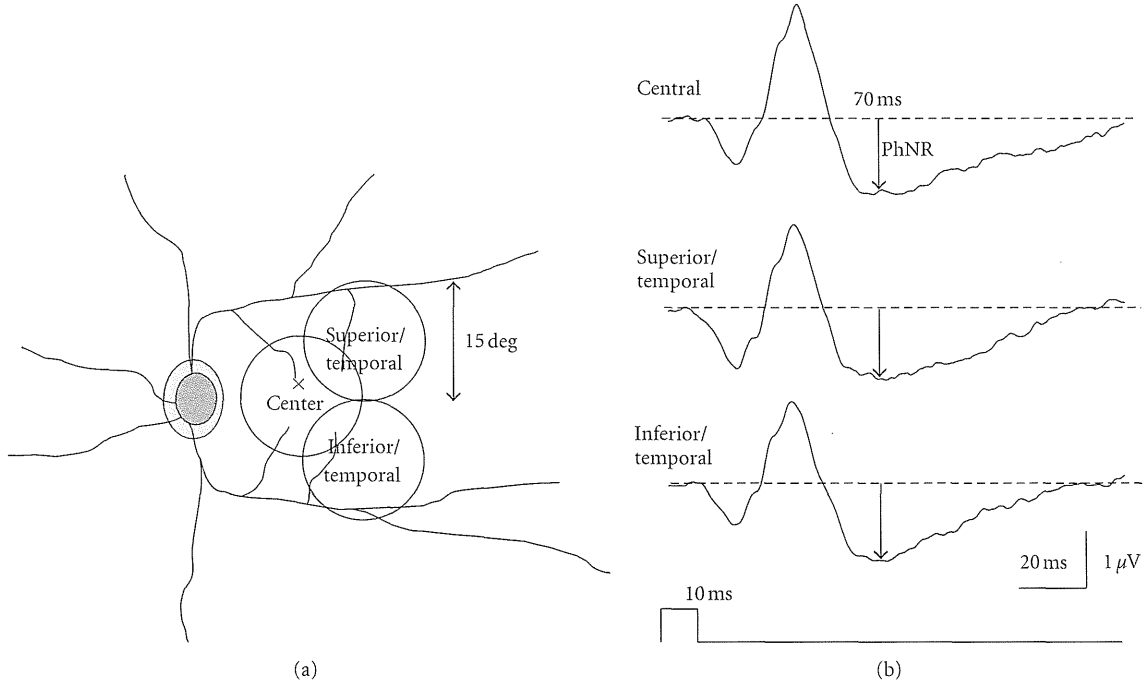

FIGURE 7: (a) Recording sites of focal electroretinograms. (b) Representative waveforms of the focal electroretinogram recorded from a normal subject. PhNR: photopic negative response.

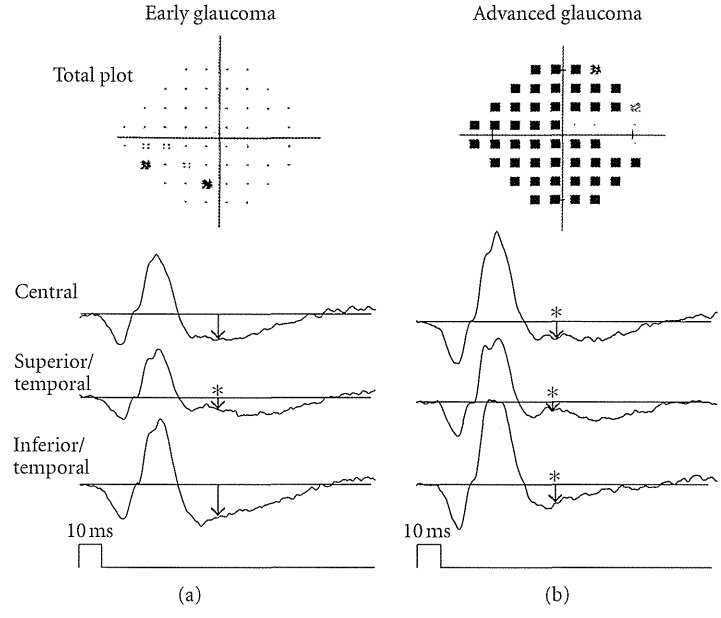

FIGURE 8: Representative cases of early (a) and advanced (b) glaucoma (reproduced with permission from [28]).

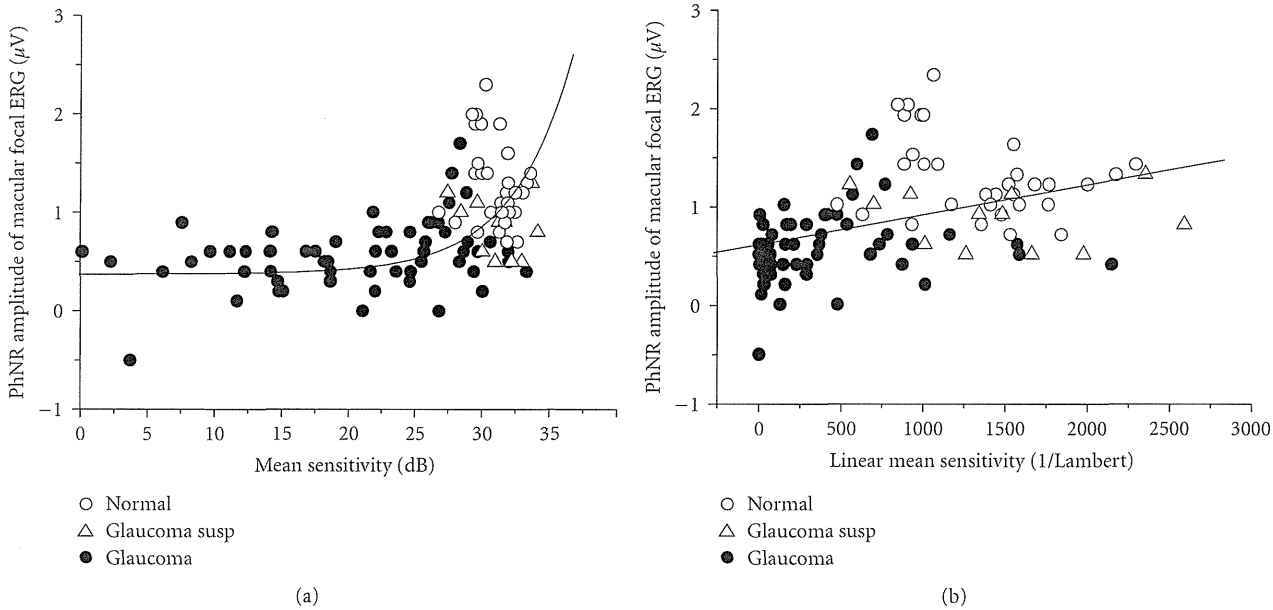

FIGURE 9: (a) The PhNR amplitude of the focal macular electroretinogram was plotted against mean visual sensitivity (dB) obtained by standard automated perimetry 10-2 program. The fitting curve was obtained by the equation based on Hood model [29, 30]. (b) The mean visual sensitivity (dB) was converted to a linear value (1/Lambert). PhNR: photopic negative response (reproduced with permission from [31]).

used for this purpose. The curve in Figure 9(a) was fit to the following equation based on the Hood model [29, 30]:

$$R = A \times 10^{0.1(S-30)} + B, \quad (1)$$

where R is the focal PhNR amplitude; A is the focal PhNR amplitude of normal RGCs; S is mean of visual sensitivity determined by SAP; B is the basal level of the focal PhNR amplitude when a patient has lost sensitivity to light.

The fact that the focal PhNR amplitude and visual sensitivity (dB) have a nonlinear relationship can be attributed to the fact that dB is a logarithmic value that can be expressed as follows:

$$\text{dB} = 10\log\left(\frac{1}{\text{Lambert}}\right) \therefore \frac{1}{\text{Lambert}} = 10^{0.1\times\text{dB}}. \quad (2)$$

When converting the visual sensitivity (dB) from a log value to a linear value (1/Lambert) using the previously mentioned

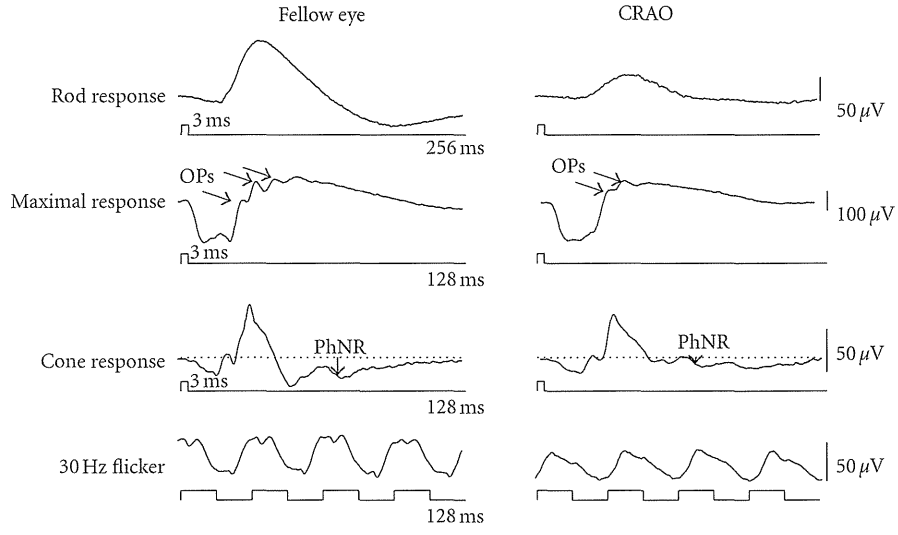

FIGURE 10: Representative waveforms of the full-field electroretinogram recorded from unaffected fellow and affected eyes with central retinal artery occlusion (CRAO). OPs: oscillatory potentials, PhNR: photopic negative response.

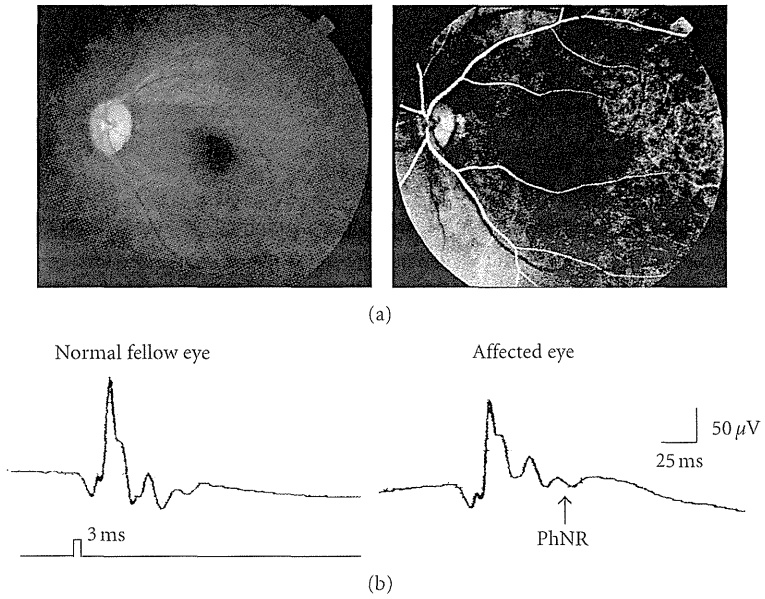

FIGURE 11: (a) Early recanalization of blood flow was seen by fluorescein angiogram. (b) The PhNR amplitude was considerably reduced in the affected eye. PhNR: photopic negative response.

equation, the relationship between the focal PhNR amplitude and visual sensitivity became linear (Figure 9(b)). The focal PhNR amplitude is also significantly correlated with local changes in RNFLT, rim area, cup/disc area ratio, or GCC thickness [16, 32, 33]. This indicates that the focal PhNR reflects the morphological changes associated with glaucoma of local area of the retina or optic disc.

3.3. Inner Retinal Diseases. Depression of the b-wave amplitude with leaving the a-wave unchanged is a well-known ERG finding in patients with central retinal artery occlusion (CRAO). Figure 10 shows the full-field ERG recorded from the fellow eye and affected eye of a CRAO patient. Focusing on the cone response, we can see that the full-field PhNR amplitude was dramatically decreased by CRAO [34]. When the respective wave amplitudes of the CRAO eye are expressed as a ratio of those of the healthy fellow eye (i.e., amplitude ratio), it became apparent that the full-field PhNR amplitude was predominantly lower than the a- and b-wave amplitudes. This is consistent with the pathological finding that damage to the inner retinal layers

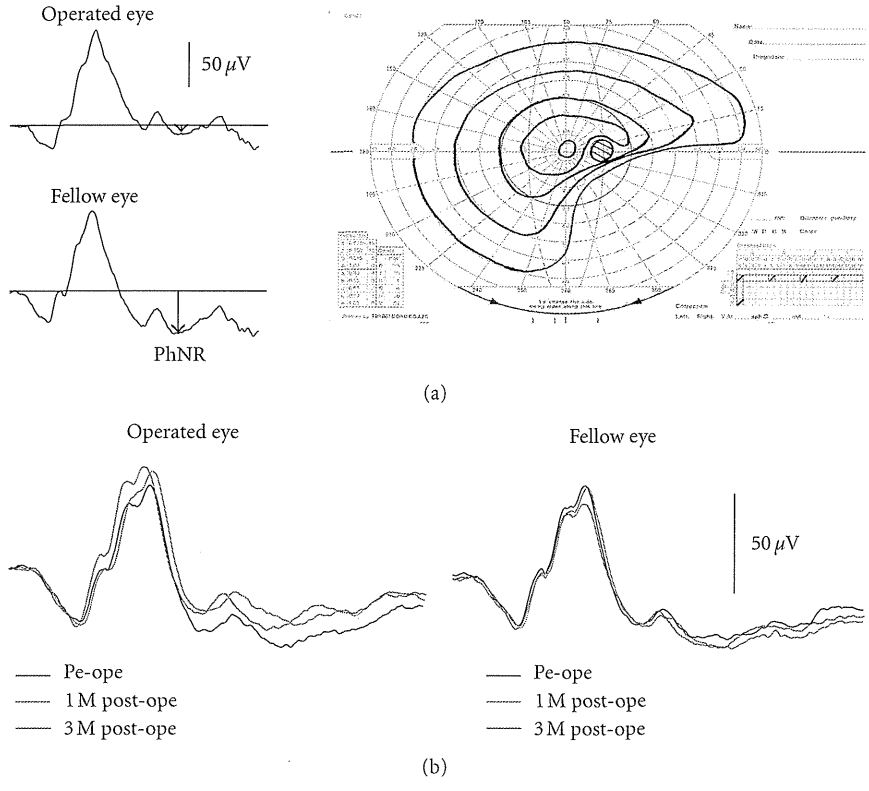

FIGURE 12: (a) Representative case of macular hole who complained of visual field defect in the operated eye after surgery. (b) Changes of the full-field cone electroretinograms recorded from a patient with a macular hole pre- and postoperatively. PhNR: photopic negative response.

is greatest among CRAO patients. When early recanalization of blood flow occurs in CRAO patients, fundus findings may be subtle (Figure 11(a)), necessitating differential diagnosis from acute optic nerve diseases. Even in these patients, however, the full-field PhNR amplitude was considerably depressed (Figure 11(b)). It has been reported that the full-field PhNR could be used to evaluate degree of ischemia or visual prognosis in patients with CRAO [35, 36].

Diminished PhNR amplitude of the full-field ERG is also observed in central retinal vein occlusion [37] and early diabetic retinopathy [38, 39]. In other words, the full-field PhNR may also be useful in the diagnosis and functional assessment of ischemic retinal diseases.

Indocyanine green (ICG) is used during macular hole surgery to visualize inner limiting membrane. The toxicity of ICG on RGCs has previously been demonstrated in an animal study [40]. The PhNR amplitude was reduced in patient who has developed visual field defects following macular hole surgery (Figure 12(a)). Ueno et al. [41] reported that the full-field PhNR was significantly reduced even in patients without developing visual field defects after surgeries. Figure 12(b) shows the time-course changes in the cone ERG before and after macular hole surgery. In the fellow eye there was virtually no change in the ERG, but in the operated eye there was a delay in the b-wave peak and slight decline in the PhNR amplitude at 1 month after surgery. At 3 months after surgery, this delay in the b-wave peak disappeared but the PhNR amplitude remained mildly depressed. While the decline in PhNR amplitude is slight, it may indicate subclinical RGC damage incurred during vitreous surgery to repair macular holes.

4. Conclusions

The use of the PhNR has enabled objective evaluation of RGC function. The PhNR can also be measured in clinical settings due to the ease with which it can be recorded and evaluated. Moreover, combining the PhNR with focal or multifocal ERG techniques enables the objective assessment of local function of RGC. The PhNR is therefore likely to become established as an objective functional test for optic nerve and retinal diseases involving RGC injury. However, further studies on the prognostic value of the PhNR in these diseases are required to establish the clinical utility of this technique.

Acknowledgments

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