Purpose. To investigate whether a rapid and practical determination of the temporal frequency characteristic (TFC) of the visual system can be obtained by using the visually evoked potentials (VEPs) elicited by pseudorandom binary sequence (PRBS) stimulation.

Methods. VEPs were recorded from eight volunteers. For the conventional steady state VEPs (S-VEP), the eye was stimulated with five stimulus frequencies. To acquire the PRBS-VEPs, the eye was stimulated with a PRBS stimulus for 40 seconds. The TFC for the S-VEP was calculated from the root mean squared amplitude for each frequency using Fourier transform. For the PRBS stimulus, a cross-correlation function between PRBS ($x(t)$) and PRBS-VEP ($y(t)$) was calculated to obtain the TFC.

Results. The TFCs obtained by the PRBS and S-VEP methods were highly correlated ($P < 0.05$), and the TFC curves resembled those in the literature. Most important, the data necessary to determine the TFCs using the PRBS stimulus could be obtained in 4 minutes, whereas that for the S-VEP required 60 minutes for the two eyes.

Conclusions. The high correlation between the TFCs obtained by the two methods indicated that the PRBS technique gives a good measure of the TFC of the human visual system. The significantly shorter time required for this method demonstrated that it is a practical method for determining the linear (and nonlinear) property of the visual system and that it may be useful in clinical applications.

**MATERIALS AND METHODS**

**Subjects**

VEPs were recorded from eight healthy volunteers (two women and six men). The corrected visual acuity of each subject was 20/20 or better, and their ages ranged from 22 to 28 years (mean, 24.5 ± 2.3 years). This research was conducted in accordance with the tenets of the Declaration of Helsinki, and written informed consent was obtained from all subjects.

**Visual Stimulation.**

Flicker stimuli were provided by an array of 15 red, light-emitting diodes (LEDs) with a wavelength of 630 nm (SES107; NEC Medical Systems, Tokyo, Japan). The LEDs were mounted in light-proof goggles and were covered with a thin, white paper diffuser to obtain unpatterned light stimuli. The array size for one eye was 1.5 cm × 2.5 cm and consisted of three rows of five LEDs. The vertical and horizontal visual angles were 60° and 70°, respectively. The mean luminance of the stimulus was 180 candela (cd)/m². The luminance was constant between 4 Hz and 32 Hz and also for the PRBS flickering condition. For all measurements, the stimuli were presented monocularly to the opened eye.

For the S-VEP recordings, the frequencies of the stimuli were 4, 8, 16, 20, and 32 Hz, and the pulses were square-wave modulated. For the PRBS-VEP recordings, the LEDs were driven by PRBS, known as m-sequence, pulses. The PRBS was generated by a 12-bit shift register with a clock interval of 10 msec, and the entire stimulus was 40,950 msec in duration. The power spectrum of the PRBS is approximately flat from the 0.024 Hz to 33.3 Hz that approximates the bandwidth of the human visual system.

The sequence of stimulation was controlled by a personal computer (PC386V; Seiko Epson, Suwa, Japan), and the LEDs were driven by an electrical power source (NEC Medical Systems) specially designed for rapid switching so that 10-msec pulses could be obtained.

**VEP Recordings and Analysis**

Bipolar VEP recordings were made between Oz (+) and Cz (-), with the right ear grounded. The VEP signal was amplified and band filtered (1-100 Hz) by a bioamplifier (MEG-1200; Nihon Koden, Tokyo, Japan), and then fed to an analog-to-digital converter (ADIX-98A, Canopus, Kobe, Japan). The sampling frequency was 1 kHz for the S-VEP and 200 Hz for the PRBS-VEP. Preliminary experiments with a higher sampling frequency of 500 Hz for the PRBS-VEPs did not change the derived first-order binary kernel and the TFCs significantly.

The S-VEPs elicited by 4-, 8-, 16-, 20-, and 32-Hz flicker stimuli were recorded independently and in random order with a recovery time of 5 minutes between changes in the frequencies. For the S-VEPs, 100 responses with a length of 0.5 seconds were averaged. The stimulus frequency component was extracted from each S-VEP by using Fourier analysis.

For the PRBS recordings, the stimulus was started 20 seconds before the initiation of data collection. For the data, the PRBS stimulus of 40,950-msec duration was repeated twice, and the two responses were averaged to obtain the final PRBS-VEP.

The human visual system for unpatterned flicker can be assumed to be a nonlinear system with one input \( x(t) \) and one output \( y(t) \). A cross-correlation function between the PRBS \( x(t) \) input and the PRBS-VEP \( y(t) \) output was calculated by Sutter’s m-transform method and the linear impulse response of the system, called the first-order kernel, was extracted from the cross-correlation function. The cross-power spectrum was then calculated as the Fourier transform of the first-order kernel using data analysis software (MATLAB; The Mathworks, Natick, MA). The cross-power spectrum was used as the TFC.

**RESULTS**

Typical S-VEPs recorded from the right and left eyes of one subject are shown in Figure 1. There was good reproducibility in the shape and amplitudes within the subject, and the correlation coefficient for each subject was higher than 0.8 for 4-, 8-, and 16-Hz stimuli. In all subjects, the shapes of the S-VEP were almost sinusoidal, and their amplitudes were highest at 8 Hz and decreased at lower and higher frequencies in both eyes. These observations are in good agreement with those in previous studies.

![Figure 1](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933210/)
FIGURE 2. (A) First-order binary kernels in the right and left eyes of one subject. The mean luminance was 180 candela/m². The shapes of kernels were similar for the two eyes. (B) The amplitudes of the cross-power spectrum obtained from pseudorandom binary sequence visual-evoked potentials (PRBS-VEPs) for the right and left eyes of one subject. The spectrum at higher than 33 Hz was discontinued because the PRBS power at higher than 33 Hz is low. Power spectrum amplitudes of S-VEP with corresponding stimulus frequency are also plotted in (B).

The first-order binary kernels and TFCs (cross-spectrum) obtained from PRBS stimulation in the right and left eyes of one subject are shown in Figures 2A and 2B, respectively. There was good agreement between the two eyes in this subject, and a match between the two eyes was found in all the other subjects. Much of the variability of the results is caused by background electroencephalograph activity. The variability was reduced significantly by cross-correlating the PRBS-VEP with the PRBS stimulus. The largest peak of the first-order kernel was a positive peak at 120 msec, which was followed by a negative trough at 160 msec.

The effect of stimulus luminance from 65 cd/m² to 185 cd/m² on the first-order binary kernel and on the TFC are shown in Figures 3A and 3B. At temporal frequencies higher than 4 Hz, the TFC curves were similar at the three stimulus luminances tested except at around 18 Hz (Fig. 3B). Similar results were obtained in other subjects.

The exact waveform of the binary kernel from the 200- to 300-msec lag and the cross spectrum from 10 Hz to 30 Hz were different among subjects (Figs. 2, 3). However, the binary kernels in all subjects had significant peaks at approximately the 120- and 160-msec lag and settled within 400 msec. Because of this reproducible settlement, the first-order kernel from the 0- to 500-msec lag was used as the linear impulse response function, and its spectrum was used as the TFC. The estimated cross-power spectrum showed a maximum amplitude at approximately 10 Hz. The spectrum had low amplitudes at frequencies higher than 33 Hz, which may be because of the low power of PRBS at higher than 33 Hz.

Examples of the TFC obtained from S-VEPs and PRBS-VEPs are shown in Figure 2B. There was good agreement of the TFCs in the two eyes and with the two techniques. The correlation coefficient between the TFCs obtained by PRBS and S-VEP was 0.95 and 0.965 in the left and right eyes, respectively. In 10 of the 16 eyes, the coefficient of correlation between the TFCs obtained by S-VEPs and by PRBS-VEPs was statistically significant ($r > 0.878; P < 0.05$). In the remaining subjects, the correlation coefficient was not lower than 0.73. This high correlation between the TFCs obtained by PRBS and by S-VEP indicated that the PRBS method was an appropriate technique for determining the TFC.

To estimate the normal variations in the TFCs determined by the two methods, all the TFC curves of the normal volunteers were averaged; the means and standard deviations are shown in Figure 4. Although the overall shapes of these curves for the two methods were similar, there is considerably more information in the curve obtained by the PRBS-VEP method.

DISCUSSION

The TFC determined by the conventional S-VEP method represents the linear characteristic of the VEP system because the linear responses in the S-VEP to several frequencies are plotted to obtain the conventional TFC (plots in Fig. 2B). In our PRBS technique, both linear and nonlinear responses were measured, but for this study, we extracted only the linear component (first-order binary kernel) to compare the TFC with that...
obtained by the S-VEP method. The TFCs obtained by both PRBS- and S-VEP methods were highly correlated (Figs. 2B, 4), showing that the PRBS method provided a good measure of the TFC of the visual system. However, more data are needed to determine whether the TFC obtained by PRBS-VEPs is a valid measure of the TFC of the visual system.

Our results showed that the PRBS-VEP method required a significantly shorter time than the conventional S-VEP method. To obtain the TFC by the S-VEP method, it took approximately 30 minutes to acquire the VEPs at the five frequencies in one eye. In contrast, the PRBS-VEP method took 2 minutes in each eye, which included a 20-second prerecording period and an 80-second period of recording. Thus, it required approximately 60 minutes to obtain the data with the S-VEP method and 4 minutes with the PRBS method in the two eyes. From a clinical viewpoint, this difference in recording time is especially significant.

The sweep-VEP technique has been used to determine the spatial frequency characteristic and the contrast sensitivity functions of the human visual system. The time required for these determinations was significantly shorter (10 seconds) than ours. However, different results could be obtained according to the rate and direction of stimulus sweep and the starting point (value) of the stimulus. With our method, because PRBS is a random sequence, stable results could be obtained.

In addition to the shorter time required with the PRBS technique, the TFCs obtained by our method provided a more detailed description of the curve. In our experiment, the frequency resolution with the PRBS-VEP was 2 Hz (0.5 seconds), whereas the TFC curve determined by S-VEPs had only five data points for frequencies ranging from 4 Hz to 32 Hz. In addition, the resolution of the PRBS method can be improved by increasing the sampling frequency. This difference in the temporal resolution of the two methods was very evident in our results. We found that the TFCs obtained from PRBS-VEP showed a significant peak at 10 Hz which was not presented in the TFCs determined by S-VEPs at 20 Hz which was not seen in the TFCs determined by S-VEPs but has also been reported in previous studies.

Noise reduction is also important in studying VEPs because the signal-to-noise ratio of the human visual system is generally low. This low signal-to-noise ratio in the VEPs results from the background electroencephalograph activity, which is usually greater than the amplitude of the VEPs. The signal-to-noise ratio improvements of the S-VEP and PRBS-VEP in this study were 10 and 12.8 times, respectively, indicating that the PRBS-VEP method was equivalent to S-VEP or slightly more effective.

PRBS stimulation has been used to elicit VEPs, and the characteristics of the kernels have been discussed. A comparison of the estimated linear impulse response function (first-order kernel) to the transient VEP has also been performed in healthy volunteers and patients. However, in these studies a short-duration PRBS stimulus was used so that the linear and nonlinear kernels overlapped and could not be estimated separately, because all kernels were lined up in the first cross-correlation function. Other investigators of the VEP system used a sufficiently long pseudorandom sequence, and derived both the linear and nonlinear kernels with a minimum estimation error. However, they presented only a brief discussion on the frequency response function of the visual system.

In our experiment, a long-duration PRBS stimulus was selected to obtain a better estimation of the linear and nonlinear kernels, and reproducible TFCs were obtained. The selected PRBS of 40,950 msec (1212 - 1) X 10 msec duration was long enough to extract the first- and second-order kernels. The first-order kernel settled between 300 and 400 msec and was not contaminated by second- and higher order (nonlinear) kernels. The first-order kernel corresponds to the impulse response function of the linear part of the system and described the same characteristics as those obtained from the conventional S-VEP method.

The VEPs elicited by unpatterned light stimuli realized by the use of diffusers allowed the determination of the temporal frequency characteristics without being influenced by the spatial frequency. Our results showed that the estimated kernels

**FIGURE 4.** The mean and SD of the temporal frequency characteristics (TFCs) determined from (A) steady state visual evoked potentials (S-VEPs) and from (B) pseudorandom binary sequence visual evoked potentials (PRBS-VEPs) in all eight healthy volunteers. The TFCs derived from the PRBS-VEPs provided a more detailed description of the TFC than did the one derived from the S-VEPs.
were reproducible within a subject, and luminance changes altered only part of the TFC (Fig. 3). These results suggest that our method could be useful for testing subjects with refractive errors or clouding of the lens (cataracts).

CONCLUSIONS

A technique using PRBS stimulation was used to determine the TFCs of the visual system. The results were compared to the TFCs obtained by the conventional S-VEP method. The TFCs obtained by both methods were highly correlated and were reliable and stable. This indicates that the PRBS method provided a practical measure of the TFC of the visual system. Most important, the PRBS method can be completed in a significantly shorter time than the S-VEP method (4 versus 60 minutes). Therefore, PRBS-VEP was a practical method that could be useful in clinical applications.

References


