What monitor can replace the cathode-ray tube for visual stimulation to elicit multifocal electroretinograms?

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To compare a conventional cathode-ray tube (CRT) screen to organic light-emitting diode (OLED) and liquid crystal display (LCD) screens as visual stimulators to elicit multifocal electroretinograms (mfERGs), mfERGs were recorded from seven eyes of seven healthy volunteers (21 ± 2 years). The mfERGs elicited by a conventional CRT screen (S710, Compaq Computer Co.) were compared to those elicited by a studio-grade master OLED monitor (PVM-1741, Sony, Japan) and a conventional LCD (S1721, Flexscan, Eizo Nanao Corp., Japan). The luminance changes of each monitor were measured with a photodiode. CRT, OLED, and LCD screens with a frame frequency of 60 Hz were studied. A hexagonal stimulus array with 61 stimulus elements was created on each monitor. The serial white stimuli of the OLED screen at 60 Hz did not fuse, and that of the LCD screens fused. The amplitudes of P1 and P2 of the first-order kernels of the mfERGs were not significantly different from those elicited by the CRT and OLED screens, and the P1 amplitude of the first-order kernel elicited by the LCD stimuli was significantly smaller than that elicited by the CRT in all the groups of the averaged hexagonal elements. The implicit times were approximately 10 ms longer in almost all components elicited by the LCD screen compared to those elicited by the CRT screen. The mfERGs elicited by monitors other than the CRT should be carefully interpreted, especially those elicited by LCD screens. The OLED had good performance, and we conclude that it can replace the CRT as a stimulator for mfERGs; however, a collection of normative data is recommended.

Introduction

Multifocal electroretinograms (mfERGs) are the electrophysiologic responses elicited by stimulating focal areas of the retina (Hood, Odel, Chen, & Winn, 2003; Shimada, 2002; E. Sutter, 2000). The stimuli used to elicit mfERGs are comprised of 61 hexagons, and the sizes of the hexagons are scaled to elicit approximately the same amplitude mfERGs across the visual field. The white (luminance on) or black (luminance off) hexagon with a base period of 16.667 ms, the

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duration of one frame, was generated on cathode-ray tube (CRT) screens, but CRTs have recently been replaced by liquid crystal display (LCD) screens. However, LCDs as visual stimulators have an inherent problem because it takes several milliseconds for the crystal molecules to change their alignment to permit the light to pass through the polarizing filter (http://www.sharp.co.jp/products/lcd/tech/s2_1.html) (den Boer, 2005; Elze, 2010). In the International Society for Clinical Electrophysiology of Vision (ISCEV) standard for clinical mfERGs (Hood et al., 2012), the potential problem with using a monitor other than a CRT is mentioned because the response time of the display screens must be very short. LCD panels typically switch between states and remain dark or bright for most of the frame. The response times should be considerably less than the frame interval, e.g., 16.667 ms for a frame rate of 60 Hz. Therefore, we paid special attention to the display characteristics of the different stimulus screens. The rise and fall times of the LCD luminance responses take several milliseconds. So the duration that a single frame displays white, maximal luminance (on-luminance) may be over 20 ms; thereby the consecutive stimuli with a base period of 16.667 ms for each hexagon may fuse, and the fusion can produce a different stimulus pattern, for example "white and white" instead of "white and black." This would be expected to have a profound effect on the mfERGs.

Recently, new screens—an organic electroluminescence screen or an organic light-emitting diode (OLED) screen—have been developed, and these screens are replacing the LCD screens. An OLED screen consists of light-emitting diodes in which the emissive electroluminescence layer is a film of an organic compound that emits light in response to an electric current. OLED technology has many promising properties for vision research, including self-emitting pixels, fast response times, wide color gamut, and high contrast. Its fast response time is expected to prevent fusion of consecutive stimuli. These properties make OLED screens suitable or even preferable to other screens, including the LCD screens, to replace CRTs for experimental and clinical use, including for eliciting mfERGs.

The aim of this study was to compare the electronic characteristics of OLED, LCD, and conventional CRT screens and also to compare the mfERGs elicited by the images created on these three types of screens.

Subjects and methods

Subjects

mfERGs were recorded from seven eyes of seven healthy volunteers who did not have any ocular diseases except for refractive errors. The volunteers consisted of four men and three women whose mean age was 22 ± 0.9 years (± standard deviation) with a range of 21–23 years. The procedures conformed to the tenets of the Declaration of Helsinki, and this study was approved by the Institutional Review Board of Teikyo University. An informed consent was obtained from all of the subjects after an explanation of the purpose of the study, procedures to be used, and possible complications.

Screen	Stimulus white (cd/m^2)	Stimulus black (cd/m^2)	Background gray (cd/m^2)
CRT	153	3	37
OLED	151	3	40
LCD	150	3	40

Table 1. Mean luminance of single hexagon in each screen.

Methods

Measurements of luminance of a single hexagon and evaluation of characteristics of each type of monitor screen

To determine the time characteristics of each monitor, the change in the luminance of a single hexagon was measured with a photodiode (S1133, Hamamatsu Photonics Co. Ltd., Hamamatsu, Japan). The photodiode was attached to the upper left corner of the single hexagon. Five measurements of the same hexagon were averaged. In addition, the luminance at the four corners and the center of the entire screen was measured with a luminance meter (CA-100S, Konica Minolta, Inc., Osaka, Japan). The variations in the averaged luminance between the center and the periphery were within 15% for each type of monitor, which complies with the standards of the ISCEV guidelines (Hood et al., 2012).

The averaged luminance of each screen is shown in Table 1. Although the luminance of the OLED screen could be set to be blacker than the other screens, it was set to be equal to that of the LCD and CRT screens.

The luminance and contrast of the CRT, OLED, and LCD screens were matched by adjusting the contrast and brightness setting of each screen. The contrast between the black and white checks was calculated with the Michelson contrast formula (Michelson, 1927) and set to be >90% for all screens in accordance with the ISCEV guidelines for mfERGs (Hood et al., 2012).

The scanning line start of all of the screens starts at the upper left side of the screen and finishes at the lower right side of the screen. It takes 16.6 ms for one scan across the screen. We measured the luminance change at five points: the four corners and the center. Because random graphic signals were not necessary, we used a

visual stimulator generator (ViSaGe, Cambridge Research System, Rochester, UK) to generate the trigger pulses and a similar array of 61 hexagons to generate reversal and not randomized checkerboard patterns. The ViSaGe generated the trigger pulse for the onset of the luminance change of the array of 61 hexagons at a frame rate of 60 Hz. The graphic resolution was set at 640 × 480 pixels for a full screen size. We defined the input lag as the difference between the onset of the trigger pulse and the beginning of the luminance change of each screen. We found that the input lag differed depending on the screen location for all three monitors. But the difference in the input lag between two specific locations was constant for all three monitors. For example, the input lag at the upper left corner, center, and the lower right corner was 0, 0 + 8.3, and 0 + 16.7 ms, respectively, for the CRT and LCD screens and 9.2, 9.2 + 8.3, 9.2 + 16.7 ms, respectively, for the OLED screen.

mfERGs elicited by 61 hexagon stimuli

All mfERGs were recorded with the VERIS Science 4.1 system (Mayo Corporation, Nagoya, Japan). The stimulus consisted of 61 black and white hexagons made by 640 × 480 pixels either on a CRT screen (17-in., 320 × 230 mm, S710, Compaq Computer Co.), an LCD screen (S1721, Flexscan, 17-in., 337 mm × 270 mm, Eizo Nanao Corp., Tokyo, Japan), or an OLED screen (PVM-1741, Sony Co., 17-in., 365.7 × 205.7 mm, Tokyo, Japan). All of the screens are commercially available. The size of the hexagons was scaled with eccentricity to elicit approximately the same amplitude mfERGs across the visual field following the ISCEV recommendations (Hood et al., 2012). The luminance of each hexagon was modulated in time by a complete m-sequence cycle of $2^{14} - 1$ elements (Sutter & Tran, 1992). The same m-sequence was used for all hexagons, but its starting point was displaced in time from one hexagon to the other. States 1 and −1 of the m-sequence represented the flash-on and flash-off periods, respectively. The base period was 16.667 ms, the duration of one frame. The CRT and LCD screens' resolution was set at 640 × 480 pixels scaled for the full screen size. The 61-hexagon frame array was presented at a frame rate of 60 Hz for both the CRT and LCD screens.

The maximum resolution of the OLED screen is 1920 × 1080 pixels, and the array of 61 hexagon elements (Figure 1) was generated at a frame rate of 60 Hz at the center by an analog component input adaptor (BKM-229X Sony, Tokyo, Japan). The graphic resolution was set at 640 × 480 pixels for the full screen size at a frame rate of 60 Hz because the analog input adaptor (BKM-229X) can only support the VERIS Science graphic signals with these specifications.

All screens were driven at a frame rate of 60 Hz although the standard frequency used to elicit mfERGs is 75 Hz. However, this frequency is not the input standard for the present OLED monitors with an analog component input adaptor. Therefore, we used a frame rate of 60 Hz for the three monitors studied.

The distance from the screen to the eye was changed for each screen to set the visual angle of the stimulus array to 45°. A chin rest and headrest was used for fixing the head position of the volunteer (HE-285, Handaya, Tokyo, Japan). The distance from the screen to the eye was 320 mm for the CRT, 340 mm for the LCD, and 280 mm for the OLED screens. Lenses of +3.0, +3.0, +3.5 D were placed before the eyes to reduce the need for accommodation during the examination with the CRT, OLED, and LCD screens, respectively.

The timing of the trigger is unknown in the VERIS system because it is controlled internally. Therefore, we defined the trigger pulse as the starting point of the luminance change at the upper left corner on the CRT monitor. We prepared two photo sensors and placed them on the CRT and LCD or the CRT and OLED screens (Figure 2). Then, the starting point of the luminance change in the CRT monitor was used as the trigger pulse for the other screens.

The response time was defined as the time it took for one pixel to turn from white to black or black to white. Other investigators have considered the response time to be the time required to change from gray to gray (Hood et al., 2003; Shimada, 2002). The response time between black-white-black was 25 ms for the LCD screen according to the manufacturer's information. There was no information on the response time for the CRT and OLED screens from the manufacturer.

mfERG recordings

All recordings were performed under room light of 104 lux, and the subjects were preadapted to the room lighting before beginning the recordings. A small black fixation point was positioned at the center of the central hexagon of the stimulus screen, and the subjects were instructed to fixate the point or the center of the screen and to try not to blink. The subjects wore their best refractive correction, and all recordings were monocular.

The recording electrode was a Burian-Allen bipolar contact lens electrode placed on the cornea. The ground electrode was placed on the right earlobe. Signals were amplified 100,000 times (RA-200 amplifier, Mayo Corp., Nagoya, Japan) and band-pass filtered from 10 to 300 Hz. No artifact rejection or spatial averaging was used to record the mfERGs. The first-order kernel and the second-order kernels were extracted by using Veris Science ver. 4.1 software to evaluate the mfERGs. An overall recording time of 4 min divided into eight short 30-s segments was used.

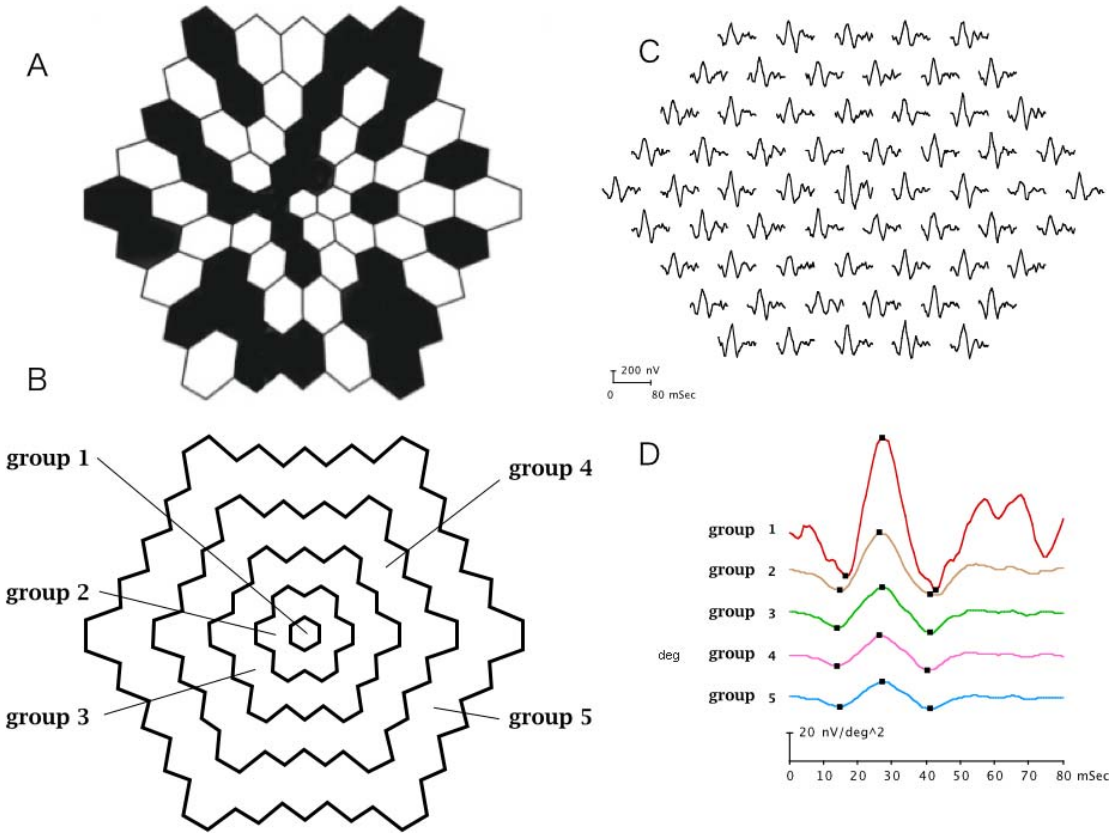

Figure 1. mfERGs and the stimulus array used to elicit the mfERGs. (A) An array of 61 hexagonal elements is displayed at the center of each screen. All screens were driven at a frame rate of 60 Hz. Although the standard frequency used for conventional mfERGs is 75 Hz, this frequency is not supported as the input standard for the presently obtainable OLED monitors that support analog RGB graphic signals. (B) The mfERGs from each hexagon in each ring were summed and then divided by the number of hexagons in the ring for the analyses. (C) The traces array is shown corresponding to the hexagonal array shown in (A). The amplitude of each wave is plotted as a potential change (voltage, nV). (D) The response density from each ring as shown in (B). The sum of the responses in each ring is divided by the total area of the hexagons in the ring and plotted as nV/deg^2.

The length of the m-sequence used in all experiments was $2^{14} - 1$. The stimulation rate was equal to 60 Hz, the frame rate of the video card. Thus, the net recording time was 4 min 33 s. The response signal was sampled synchronously with the video display at 16 samples per display time, 960 samples/s. The resulting sampling interval was 1.04 ms. The mfERGs from all of the hexagons in each ring were summed and then divided by the number of hexagons (Figure 1). This average trace array and the averaged responses from each group are shown in Figure 1.

The first-order kernel is simply the mean of the responses following all of the flashes presented during the stimulation minus the mean of the responses following the m-sequence with no flashes. The second-order kernel is the difference between the double-flash response predicted on the bases of the mean response to single flashes and the measured mean response to double flashes (Wu & Sutter, 1995, see Supplemental Figure 1).

Data analyses

The amplitudes and peak times of the first- and second-order kernels of the mfERGs were analyzed (Figure 3). The P1 amplitude was measured between the first negative trough (N1) and the first positive peak (P1); the implicit times of N1 (N1 implicit time), P1 (P1 implicit time), and the second negative component (N2 implicit time) of the first-order kernel were measured. The amplitude between the second negative component (N2) and the second positive component (P2 amplitude), the implicit times of the first negative component (N1 implicit time), first positive component (P1 implicit time), N2 (N2 implicit time), and P2 (P2 implicit time) of the second-order kernel were also measured.

Student's t tests were used to determine the significance of differences of each parameter. A $p < 0.05$ was taken to be significant.

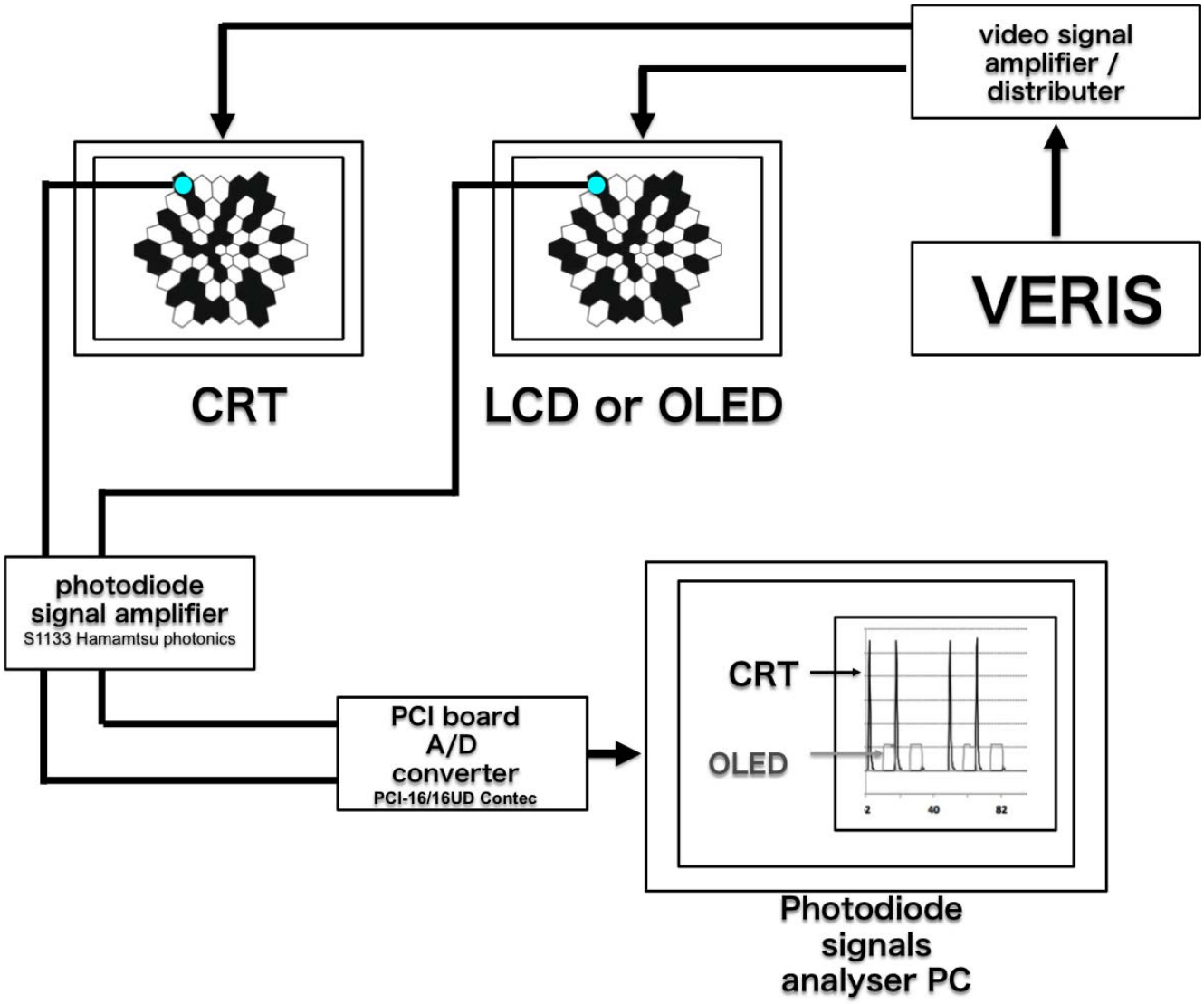

Figure 2. Measurement of the time difference of the starting point of the luminance change among the monitors. Because the timing of the trigger is unknown for the VERIS system, the time difference of the starting point of the LCD or OLED from that of the CRT was measured. Two photosensors were placed on the CRT and LCD screens or the CRT and OLED screens. Then, the start of the luminance change at the upper left corner on the CRT monitor was used as the trigger pulse for the other screens.

Results

Luminance changes of a single hexagon on each monitor

The changes in the luminance of a single hexagon on each monitor are plotted against time in Figure 4A. A burst of pulses at 60 Hz was delivered to the CRT, LCD, and OLED screens to change the luminance of the hexagonal elements. Careful examination of the luminance showed that there was a time difference between the trigger pulse and the beginning of the luminance change (Figure 4B). This difference was called the input lag (Brainard, Pelli, & Robson, 2002; Nagy et al., 2011). The input lag of the LCD screen was identical to that of the CRT screen, and there was a delay of 9.2 ms for the OLED screen (Figure 4B). The reason for this lag is that the trigger signal is further processed at the display level before it appears on the OLED screen. It is important to remember that the image-processing technologies and processing times can vary with the manufacturer, display type, and setup parameters, such as the resolution, color settings, and internal processing (Artamonov, 2007). Because the input lag was constant for the monitors, it was subtracted from the implicit time in the analyses of the mfERGs (Figure 5).

The lag time is approximately 9.2 ms for the OLED and 0 ms for the LCD screen. The timing of the trigger

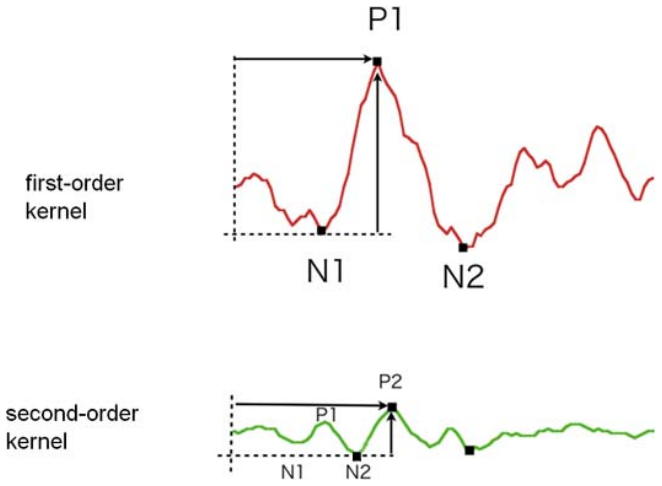

Figure 3. mfERGs recorded from a normal subject. Upper: First-order kernel of mfERGs showing the N1, P1, and N2 components. The vertical arrow shows the peak amplitude, and the horizontal arrow shows the implicit time of P1. Lower: Second-order kernel mfERGs showing the N1, P1, N2, and P2 components. The vertical arrow shows the peak amplitude, and the horizontal arrow shows the implicit time of P2.

is unknown for the VERIS system because it is controlled internally. Therefore, we defined the input lag as the time difference from the trigger pulse, the starting point of the luminance change in the CRT screen, and the beginning of the luminance change of the OLED and LCD screens. Measurements of the luminance at the four corners and center of the entire screen confirmed that the time lag of the luminance change at different locations was constant.

The input lag of the OLED was longer than that of the CRT, but the response time was fast enough so that the serial white stimuli at 60 Hz did not fuse. The LCD screens had a slow response time; therefore, the serial white stimuli fused.

During the reversal phase, the luminance change was delayed in the LCD screen especially from black to white. The delay was caused by the time for the liquid crystal molecules to line up to permit light to pass through the polarizing layers. The change in the luminance on the ascending slope was unique to a specific LCD screen. The delay was asymmetrical between black to white and white to black, which led to a transient reduction in the mean luminance of the entire screen. In contrast, the ascending slope of the luminance change from black to white and the descending slope from white to black were very rapid and symmetrical in the OLED screen. In the CRT screen, the ascending slope and descending slope were asymmetrical. Both were very sharp compared to those in the LCD screen.

The input lag was longer in the OLED compared to the LCD and CRT. However, the response time was fast enough in the OLED so that the serial white stimuli at 60 Hz did not fuse. In contrast, the LCD screen had a 0-ms input lag but the longest response time; therefore, the serial white stimuli fused (Figure 4A).

Comparisons of mfERGs elicited by OLED, LCD, and CRT screens

Reproducible mfERGs were recorded using each monitor (Figure 6). The averaged responses in the ring analysis for the first- and second-order kernels elicited by each monitor are shown in Figure 7. The P1 amplitude and the N1, P1, and N2 implicit times of the first-order kernels are plotted in Figure 8. The input lag of 9.2 ms for the OLED monitor was subtracted from the measured times (see previous section). No significant difference was observed between the P1 amplitude of the first-order kernel elicited by the OLED from that elicited by the CRT. However, the P1 amplitude of the first-order kernel elicited by the LCD stimuli was significantly smaller than that elicited by the CRT in all of the groups of the averaged hexagonal elements (Figure 8A). When compared to the mfERGs recorded elicited by the CRT screen, the N1, P1, and N2 implicit times of the first-order kernels were delayed in the mfERG elicited by the LCD in all of the rings. However, significant differences were observed only in a few implicit time measurements: the N1 implicit time from rings 2, 4, and 5 and the P1 implicit time from ring 5 between CRT and OLED monitors (Figure 8B through D).

The P2 amplitude and the P1, N2, and P2 implicit times of the second-order kernels are plotted in Figure 9. The differences in the P1 amplitudes elicited by the CRT, OLED, and LCD screens were not significant. The P2 amplitude of the second-order kernel in rings 3 and 5 of the averaged hexagons elicited by the LCD screen was significantly smaller than that elicited by the CRT screen, and no significant difference was found in the P2 elicited by the CRT and OLED screens. The implicit time of the P1 of the second-order kernel elicited by the LCD screens was significantly longer than that elicited by the CRT screen in rings 1, 2, 4, and 5 of the averaged hexagonal elements. The implicit time of P2 of the second-order kernel elicited by the LCD screen was significantly longer than that elicited by the CRT for all rings of the averaged hexagonal elements. In contrast, no significant difference was observed between the implicit times of P1 and P2 of the second-order kernel elicited by the OLED and those elicited by the CRT except that the implicit time of P1 was significantly longer compared to that by the CRT in ring 3 of the averaged hexagonal elements.

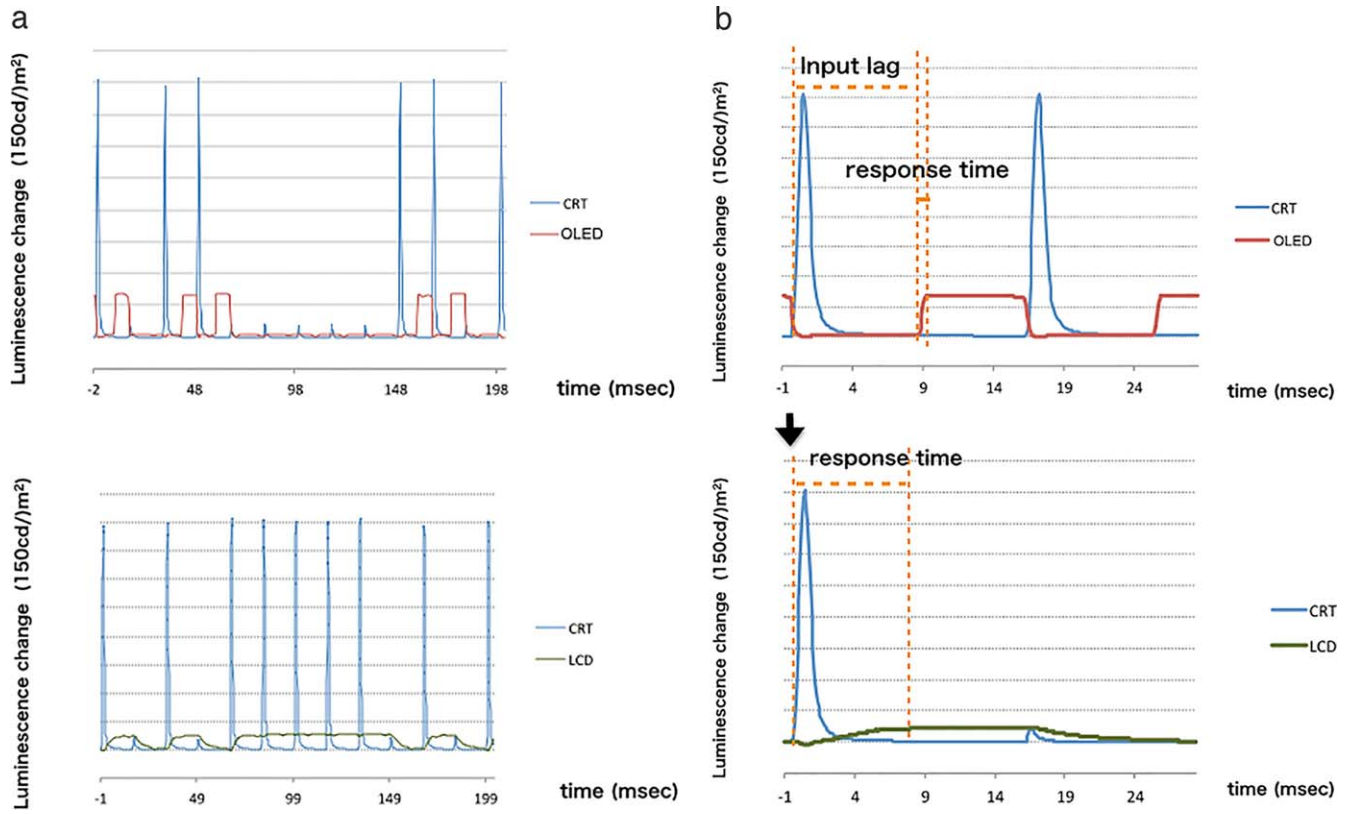

Figure 4. Changes in the luminance against time of the CRT, OLED, and LCD screens. (A) Changes in the luminance are plotted against time. Upper: The input lag of the OLED is longer than that of CRT, but the response time was fast, and the duration of the on-luminance was short enough so that the serial white stimuli did not fuse. Lower: The LCD screen had a slow response time without the input lag, and the duration of the on-luminance was long; therefore, the serial white stimuli were fused. In the LCD used in this study, the rise and fall time was 6.2 ms and 9.6 ms, respectively. Blue line: CRT screen; red line: OLED screen; green line: LCD screen. The starting point has a 1-ms difference after the raw data are shown. (B) Zooming up of the initial luminance change. The input lag is indicated by the bars. Upper: Input lag and response time for the OLED screen is indicated by the dotted line. Lower: Input lag and response time for the LCD is indicated by the dotted line.

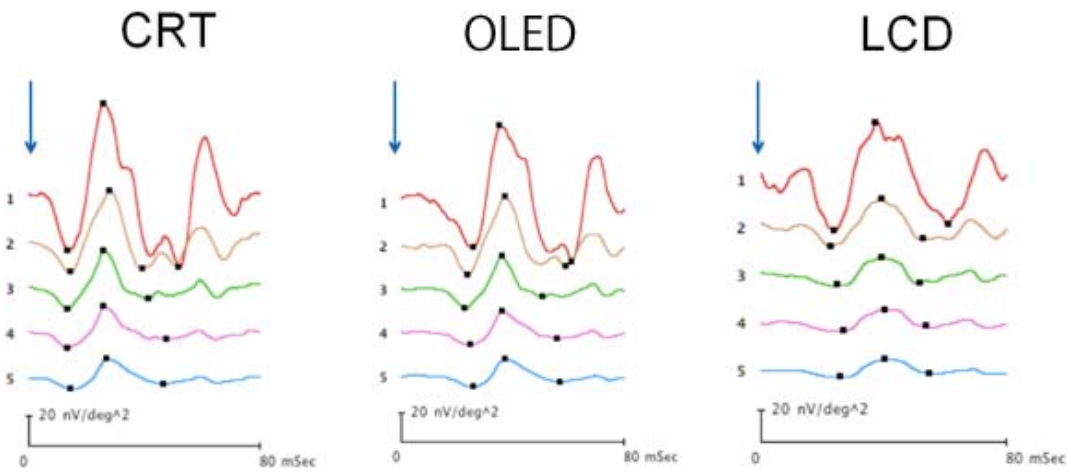

Figure 5. mfERGs in relation to the trigger onset. The input lag was constant for the screens used, and it was subtracted from the implicit times in the analyses of the mfERGs. Arrows indicate the trigger pulse.

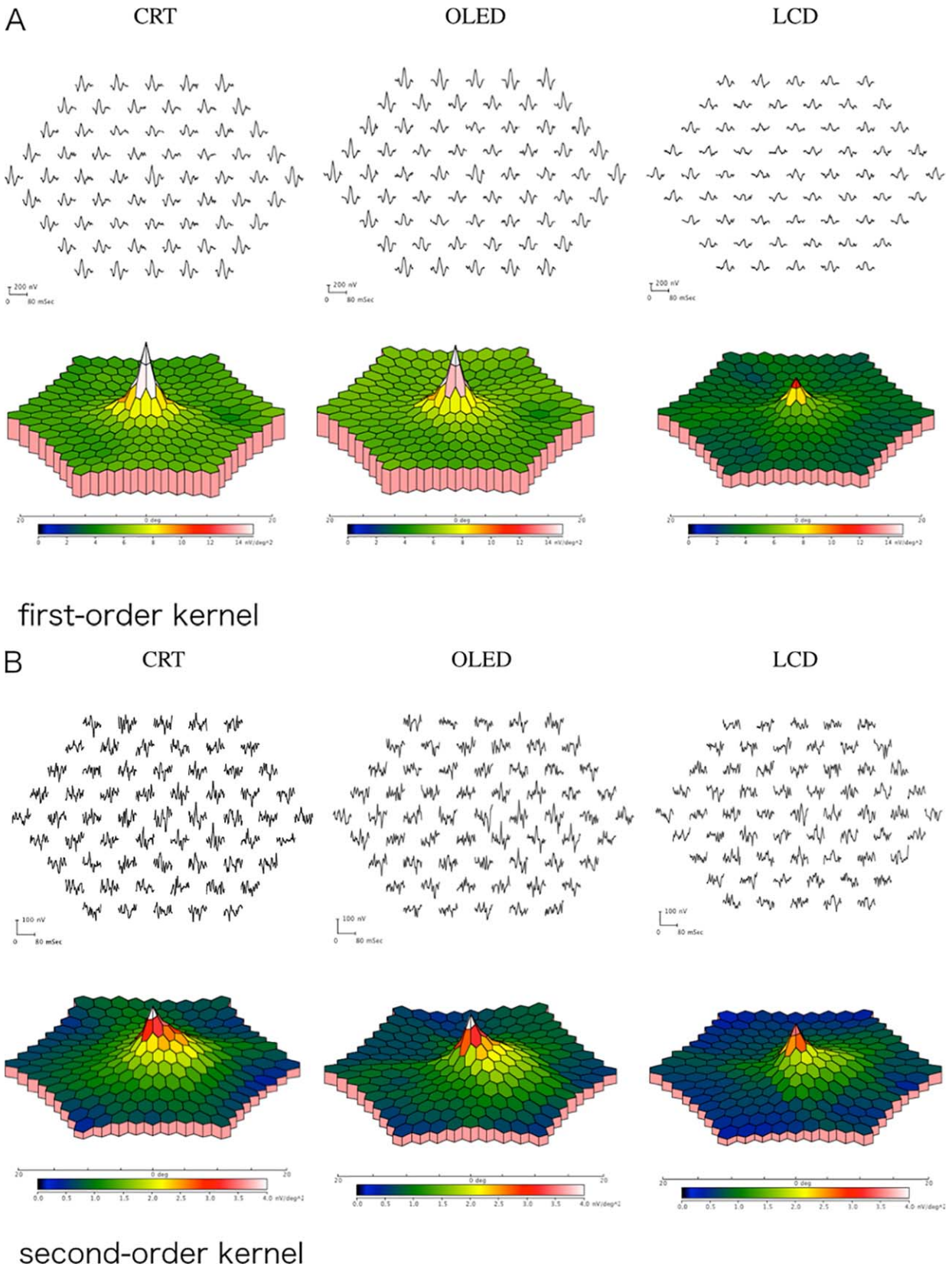

Figure 6. mfERGs elicited by the three types of screens. Left column: CRT screens; middle column: OLED screen; and right column: LCD screen. (A) First-order kernel of mfERGs. (B) Second-order kernel of mfERGs.

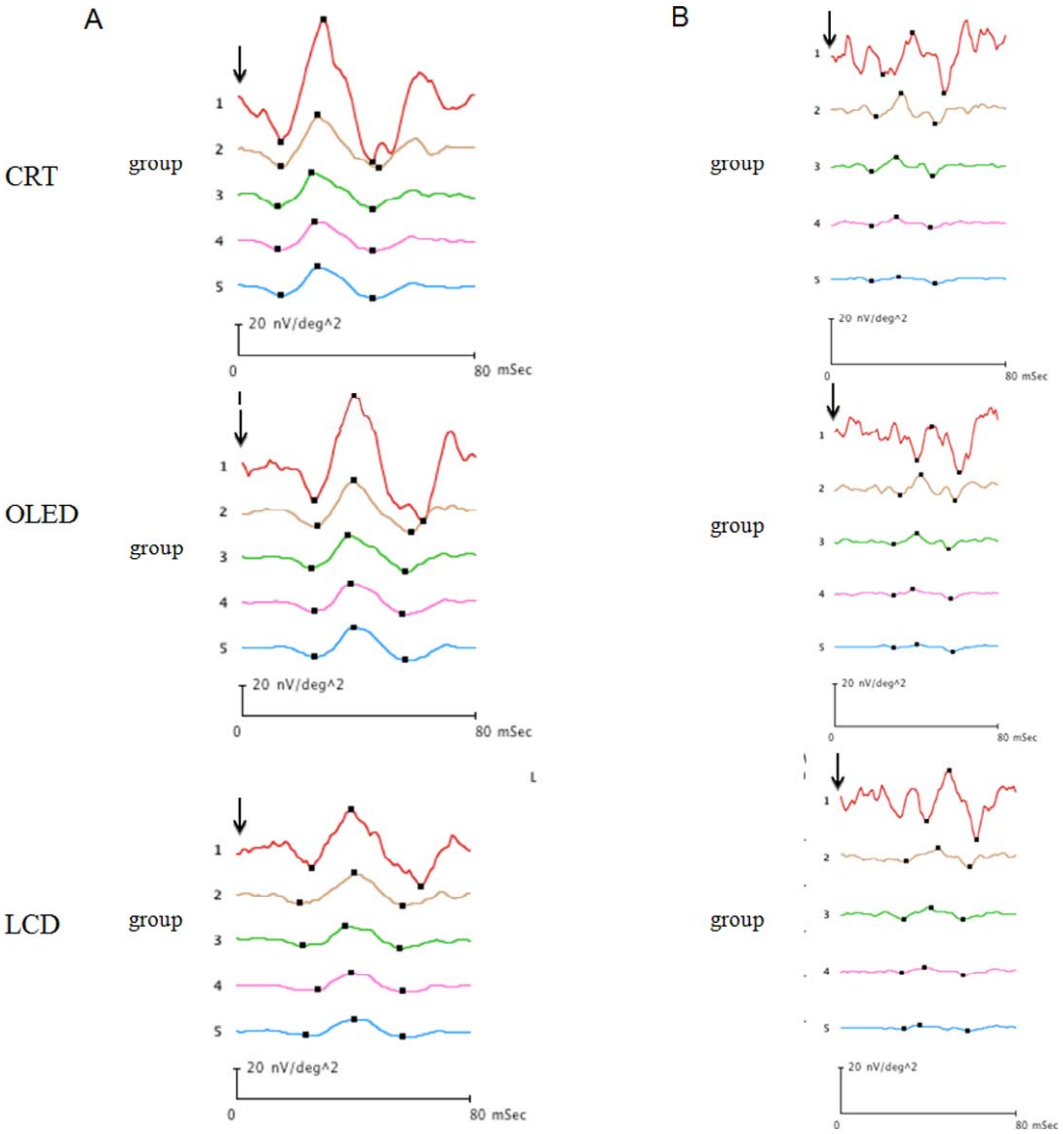

Figure 7. Ring analyses of the averaged mfERGs for the first- and second-order kernels elicited by each type of screen. Left column: first-order kernel; right column: second-order kernel; first row: CRT screen; middle row: OLED screen; third row: LCD screen.

Discussion

Our results showed that the mfERGs elicited by a stimulus array created on an OLED screen were comparable to the mfERGs elicited by a stimulus array created on a CRT screen. No significant difference was observed between the P1 amplitude of the first- and second-order kernels elicited by the OLED from that elicited by the CRT whereas the P1 amplitude of the first-order kernel elicited by the LCD stimuli was significantly smaller than that elicited by the CRT in all the groups of the averaged hexagonal elements. Only a few implicit times—the N1 implicit time from rings 2, 4, and 5 and the P1 implicit time from ring 5—were significantly different between the CRT and OLED monitors. In contrast, the N1, P1, and N2 implicit times of the first-order kernels were delayed in the mfERG elicited by the LCD in all of the rings compared to the mfERGs recorded elicited by the CRT screen. These findings indicate that the OLED screens would be better for creating stimuli to elicit mfERGs.

The use of OLED screens has expanded although there are still difficulties in producing large-size OLED screens, and their relatively high cost limits their use for television screens and computer monitors. Because OLED displays do not have a backlight, their black is blacker than that of LCD screens. Under low ambient conditions, an OLED screen can have a higher contrast than CRT and LCD screens. OLEDs also have the advantage of a faster response time than standard LCD screens. The LCD displays are capable of between 1 and 16 ms response times leading to a refresh rate of 60 to 480 Hz; however, an OLED can theoretically have

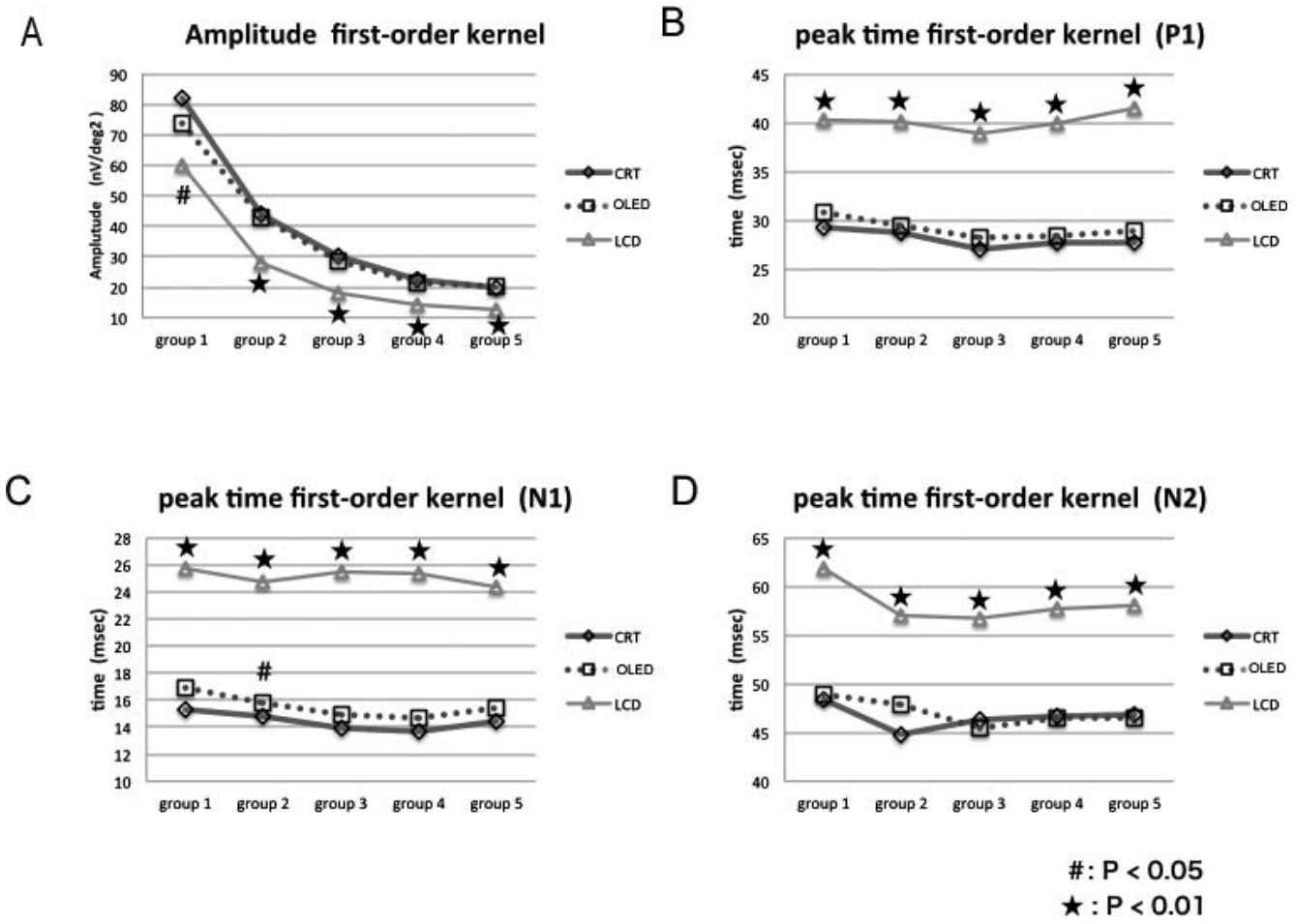

Figure 8. Measurements of the P1 amplitude and the N1, P1, and N2 implicit times of the first-order kernels. (A) No significant difference was observed in the P1 amplitude of the first-order kernel elicited by the OLED compared to that by the CRT. However, the P1 amplitude of the first-order kernel by the LCD was significantly smaller than that elicited by the CRT screen in all of the rings. (B–D) The N1, P1, and N2 implicit times of the first-order kernels were longer in the mfERGs elicited by the LCD than those elicited by the CRT screen for all rings. However, significant differences were observed in several implicit times: the N1 implicit time from rings 2, 4, and 5 and the P1 implicit times from ring 5 between the CRT and OLED screens.

less than a 0.01-ms response time enabling a refresh rate of up to 100,000 Hz. Thus, OLEDs can also be used as a flicker stimulus similar to CRTs.

The photosensor measurements showed that the luminance changes of the OLED and CRT screens were very rapid and not significantly different (Figure 4). However, the luminance changes were basically different, i.e., rectangular for the OLED and a train of bursts in CRT. The practical usefulness of these two screens can be confirmed by using them for mfERG recordings as used in routine clinical settings.

The characteristics of OLED screens have been evaluated in detail (Cooper, Jiang, Vildavski, Farrell, & Norcia, 2013; Elze, Taylor, & Bex, 2013; Ito, Ogawa, & Sunaga, 2013), and our results are in good agreement with these earlier evaluations. Recently, the characteristics of an OLED screen (Sony PVM-2541, 24.5-in.; Sony Corporation, Tokyo, Japan) have been precisely measured from the viewpoint of its applicability to visual psychophysics (Cooper et al., 2013). The tested OLED screen was reported to have excellent luminance and color uniformity; excellent low-luminance gradation; stable white and three primary colors throughout the wide luminance range; wide color space, especially for saturated green; and rapid luminance rise/fall times. The authors stated that if large enough OLED displays were constructed, it would be ideal for vision research. However, they also stated that the concept of one frame in the PVM-2541 is different from those in an LCD or CRT display, and it is unclear whether these differences will affect the human perception of short-duration stimuli.

The waveform of the mfERGs elicited by the OLED screen was comparable to that elicited by a CRT

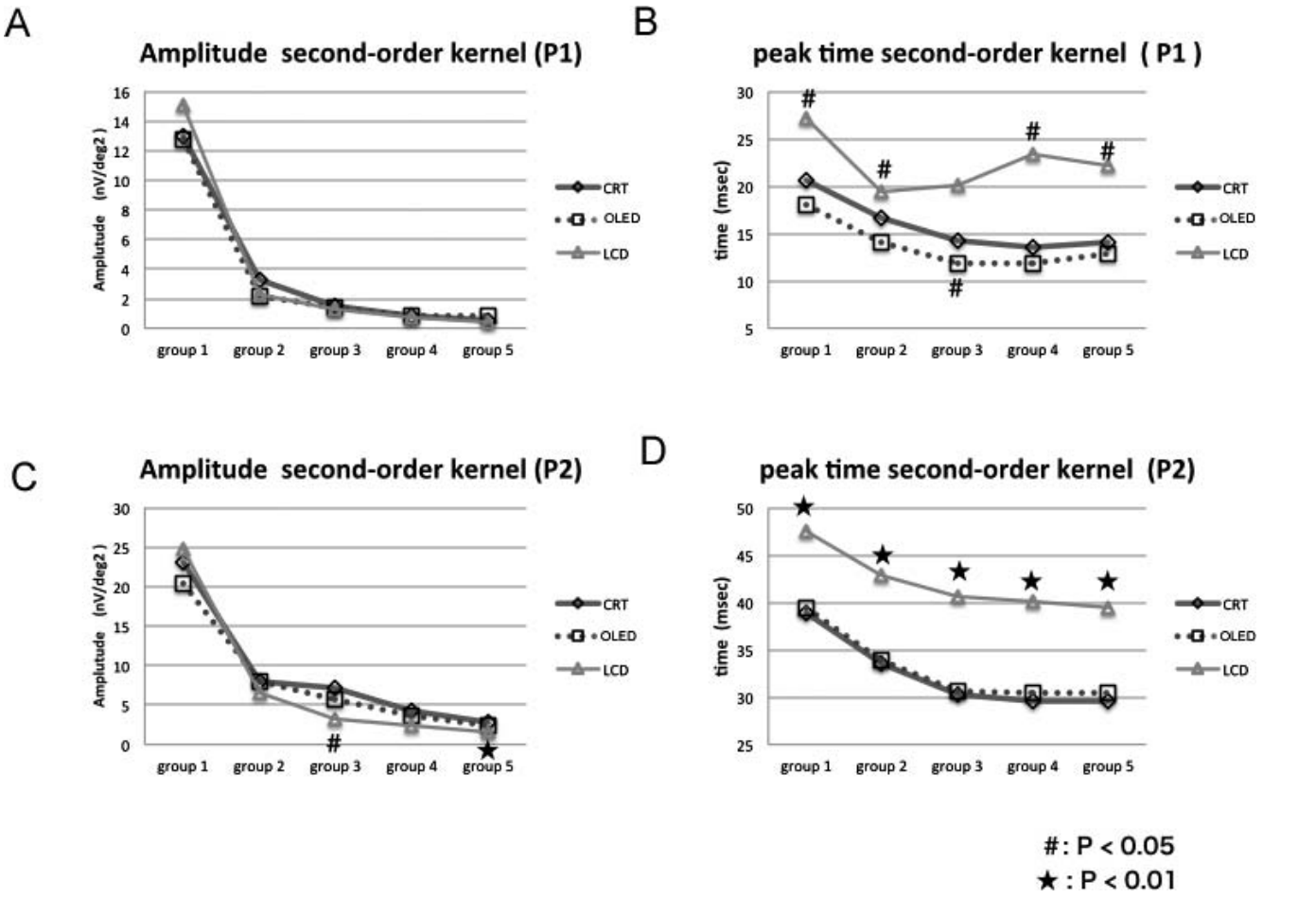

Figure 9. Measurement of the P1 and P2 amplitudes and the P1 and P2 implicit times of the second-order kernels. No significant difference was observed in the P1 amplitude of the second-order kernel in all rings between that elicited by the CRT and OLED screens and also those elicited by the CRT and LCD screens. The P2 amplitude of the second-order kernel in rings 3 and 5 of the averaged hexagonal elements of the LCD screen was significantly smaller than that elicited by the CRT screen. However, no significant difference was found between that elicited by the CRT and OLED screens. The implicit times of P1 of the second-order kernel elicited by the LCD screen were significantly longer than those elicited by the CRT screens for rings 1, 2, 4, and 5 of the averaged hexagonal elements. The implicit times of P2 of the second-order kernel elicited by the LCD were significantly longer than those elicited by the CRT screen for all of the rings of the averaged hexagonal elements. In contrast, no significant difference was observed between the implicit times of P1 and P2 of the second-order kernels elicited by OLED and those by CRT except that the implicit time of P1 was significantly longer than that by CRT in group 3 of the averaged hexagonal elements.

screen. The amplitude of P1 and implicit times of N1, P1, and N2 of the first kernel and the amplitudes of P1 and P2 and implicit times of P1 and P2 in the second kernel elicited by the OLED screen were not significantly different from that elicited by a CRT screen.

The luminance changes in the LCDs had a relatively slow rise from black to white and slow fall from white to black. Our previous experiments (Matsumoto et al., 2013) showed that the time delay caused a transient reduction in the averaged luminance of the entire display. To reduce the transient reduction, either decreasing the contrast of the checkerboards or using higher frequency–driven LCDs would be effective. But such a setup for the LCD screen is not easy when used in clinical practice.

When examining each component of the mfERGs, the amplitude of P1 of the first-order kernel and the amplitude of P2 of the second-order kernel elicited by an LCD screen were significantly different from those elicited by a CRT. Only the P1 amplitudes in all rings and the P2 amplitudes in rings 1 and 2 of the second-order kernel were identical between the waves elicited by the LCD and CRT screens. In addition, the implicit times of all components in all of the rings were significantly delayed when the LCD was used as a stimulator compared to that when the CRT was used. This is in good accord with the results by Kaltwasser,

Horn, Kremers, and Juenemann (2009) who investigated the suitability of LCD as a visual stimulator for mfERGs. They stated that when an LCD screen was used as a stimulator, the increase in the implicit times and differences in the luminance-versus-time profile must be taken into account. Most of the LCD screens have similar properties with slow luminance rises and falls. The drive system of the LCD display used in this paper was vertical alignment (VA). This system has some advantages by having more uniform luminances and deeper black with a high contrast ratio than twisted nematic (TN) panels. The disadvantage is that they have a slower response time compared to TN panels. In the manufacturer's specifications of the LCD monitor, the response speed is reported to be 25 ms for black-white-black, which is relatively slow. We measured the rise (black to white, 10% to 90% luminance) and fall times (white to black, 90% to 10% luminance), and the results were 6.2 and 9.6 ms, respectively (Supplemental Figure 2).

A significant delay in the implicit times of the first- and second-order kernels was observed in the mfERGs elicited by the LCD system compared to that elicited by the CRT screen (Figures 8 and 9). The VA of the LCD used in this study has a 25-ms response time, and we used a 60-Hz mode of stimulation. Each sequence of 60-Hz stimulation has a 16.67-ms stimulation period; thus, the first stimulation signal will be fused onto the second signal by 8.33 ms, and this mimics the 8.33 ms of delay in the waveform. In addition, significant reductions in the amplitude of the first-order kernel were observed in the mfERGs elicited by the LCD compared to that elicited by the CRT screen (Figures 8 and 9). We believe that not only the overlapping of the preceded luminance by 8.3 ms (25 − 16.7), but also the slower rising slope of the luminances (6.2 ms) might be responsible for the delay in the implicit times and reduction in the amplitude with a greater contribution by the latter. The longer response times influenced the amplitudes but not the implicit times. Uno, Tahara, Nakao, and Otori (1999) investigated the ERG responses after photostimulation with a varying duration of rise and fall times, and they reported that an increase in the rise and fall times caused a decrease in the amplitudes and prolongation in the latencies.

We believe that the differences of the response times, rise and fall times, and durations of the on-luminance between LCD and CRT screens were the cause of the significant differences in the values of the different components of the mfERGs obtained by the LCD as opposed to those elicited by CRT screens.

The fusion of the LCD responses implies that the m-sequences underlying the multifocal technique cannot be accurately reproduced by the LCD display. Therefore, further investigations on LCD screens with a 120-Hz refresh rate and/or inserting a black frame after each stimulus frame may be helpful to solve this. In other words, our results demonstrated that no black frames are necessary with OLEDs because no fusion occurred.

The long input lag observed in the OLED is unlikely due to the OLED itself but may be due to the Sony BKM229X RGB/Component video input module signal conversion that we used to convey the analog video signal from the VERIS mfERG system for the digital display. Our results that OLED showed negligible response time is in accordance with the results of Cooper et al. (2013). However, our results differed from theirs in that they did not evaluate the effect of input lag. This is because they used the voltage change from the photodiode placed on the monitor, so the recording was triggered by the luminance change of the monitor whereas our results showed long input lag, probably due to the video module signal conversion used in this study.

OLED stimulation had 9.2 ms of delay compared to CRT stimulation. Because the duration of the on-luminance was short enough compared to the 16.67 ms in the OLED, no fusion in the consecutive on-luminance was observed. In contrast, the duration of the on-luminance was relatively long in the VA LCD; in the case of white and white, fusion at the beginning of the second frame took place. Thus, the mfERG waveforms were blunted because the stimulations could not be clearly separated as shown on Figure 4 and Supplemental Figure 2. We conclude that some of the LCD monitors may be not appropriate for eliciting mfERGs or be used with care.

There are several limitations in this study. The frequency used was not 75 Hz, which is widely used in clinical practice. The mechanism for the differences in the implicit times between mfERGs recorded using different monitors was not determined. The properties of the luminance changes were different, and their influence on the retinal response was unknown. Investigating the influence of the different properties on the human visual system will be interesting, but we have only investigated the possibility of substituting the CRT monitor with another monitor as a visual stimulator for mfERG. We investigated a single LCD and a single OLED monitor, but the input lag and response time are unique in LCD and OLED screens. Therefore, a better LCD screen or a better OLED monitor as a visual stimulator may be found with further investigations. Moreover, we only used the S1721 Flexscan LCD monitor, which is a VA type LCD. A TN LCD, which has 5 ms of response time, may minimize the overlapping and may show similar results as OLED displays. In the literature of Cooper et al. (2013), the LG Flatron D2342 LCD, one of the TN LCDs, shows increasing slope up to 5 ms and, after that, shows a plateau (saturation) response. However,

most TN LCD panels have a disadvantage in that their response time increased markedly when used under a special mode, such as fine color drawing or low-contrast conditions. Further investigations are needed to compare commercially available TN LCDs with CRTs as visual stimulators to elicit mfERGs.

In conclusion, an OLED screen is a better substitute for a CRT screen on which to create stimuli to elicit mfERGs. Although the waveforms of the mfERGs are similar, they are not completely identical. We recommend that normative mfERGs elicited by OLED screens be collected from normal eyes before the mfERGs from diseased eyes are examined.

Keywords: organic electroluminescence monitor, multifocal ERG, cathode-ray tube, liquid crystal display

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