Use of Infrared TV Cameras Built into Head-Mounted Display to Measure Torsional Eye Movements

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Purpose: The head-mounted display (HMD) has produced conflict between visual and vestibular stimuli because the HMD image does not move with the head motion of the wearer. The HMD can show binocular parallax three-dimensional (3D) images, in which vergence and accommodation conflict. Thus, the HMD may affect the normal visual/vestibular functions. We attempted to develop a system that makes possible the measurement of torsional eye movements, vergence eye movements, and pupillary responses of the HMD wearer.

Methods: Our apparatus is composed of two infrared CCD cameras installed in the HMD. Iris images produced by these cameras are analyzed by a personal computer using free software. Further, a third camera fixed on the HMD projects an image of the view as the subject sees it, via video tape recorder or frame memory to the HMD. Images can be stored, replayed, or frozen.

Results: Our system can measure torsional eye movement with 0.20° resolution every 1/30 (or 1/60) seconds even though the pupil size alternates during measurement. Binocular eye movement and pupillary response are also measured.

Conclusion: A system was developed which can be used for assessment of the effect of 3D HMD on the visual system. A third camera coupled with HMD can control visual stimulus independently of head motion (vestibular stimulus). **Jpn J Ophthalmol 2001;45:5–12**

Key Words: Counter-roll torsional eye movement, head-mounted display, image analysis, vergence eye movement, vestibulo-ocular reflex.

Introduction

It is well known that motion sickness is frequently observed among the users of virtual reality (VR) systems.[1] This VR sickness may be attributed mainly to the time delay of the feedback from the head motion to the visual image, due to computer limitations. A head-mounted display (HMD) is frequently used as the visual display in a VR system. However, when the HMD is used independently without the feedback of the head motion, motion sickness is not completely eliminated.[2] In general, the necessity of observing eye movement, especially torsional eye movement, is indicated when motion sickness is induced. A new measuring system is required in order to measure eye movement in such HMD wearers.

Two possible causes of motion sickness in HMD wearers can be assumed. One is vection, which is defined as a sensation of self-motion induced by moving visual images. The other is conflict between vestibular and visual stimuli. When the head rotates horizontally, the outer world moves horizontally in the opposite direction from the head and the eyes will follow the outer world. This counter motion is induced by the vestibular system (vestibulo-ocular reflex [VOR]), so that this eye movement is also induced even in the darkness (gain of eye/head velocity in the dark is different from the gain under illumination). However, the image on the HMD moves

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with the head. Thus, VOR gain should be zero if a stable image is desired. This phenomenon is known as visual suppression of VOR but this situation is not natural. If the head rolls, a counter-roll torsional eye movement is induced by the vestibular system. There has been no report of the visual suppression of counter-roll eye movement. It is known that the vestibular system adapts to the mismatch of VOR gain, but the adaptation of the counter-roll eye movement has not been described.

Equipment that measures eye movement, especially torsional eye movement, is required for research in this field. We have developed a new system for measuring this.

Our newly developed equipment can also measure simultaneously the change of binocular pupil area and vergence eye movement as well as torsional eye movements. In 3D displays using the binocular parallax, the conflict between convergence and accommodation has been known as the cause of asthenopia. A relationship between the complaint of asthenopia and pupil area has been indicated.[3] Therefore, our newly developed equipment can be useful for eliminating vision problems related to the use of displays in the HMD.

For the measurement of horizontal and vertical eye movements, the corneal reflex method, sclero-corneal reflectance difference (limbus tracking) method, and search coil method are known. The merits and demerits of each method are also well known. Only the search coil method and image analysis method can be adopted to measure torsional eye movements.

The search coil method[4,5] uses the potential induced by a coil put in a variable magnetic field. The potential corresponds to the angle between the magnetic field and the coil. Eye movement can be measured by measuring the direction of the coil built into a contact lens. The merits of this method are accuracy and ability to determine the absolute angle of the eyeball. However, the subject must wear a contact lens with a built-in coil, and there is the possibility of invasion into the cornea. Furthermore, the subject must stay in the center of the magnetic field.

The image analysis method analyzes the pattern of the iris or attached object on the eyeball. This method uses the unique pattern that exists in each human iris. There are different image analysis methods. In one method, a characteristic part of the pattern (eg, large black pigment part) is traced as a binary image, and the angle of the line between this part and the center of the pupil can be calculated in each image.[6,7] In this method, a measurement is possible even if the eyelid partially covers the pupil, unless the specific point is covered. Another method uses the density profile along a specific circle around the pupil as a template. This is called the polar correlation method.[8] Torsional movement of the eye induces a shift of the density profile so that a cross-correlation calculation between the template and measuring pattern makes measurement of the angle of torsion possible. Thus, the amount of shift that brings about the highest correlation shows the angle of torsion. However, the actual iris moves actively and the pupil diameter changes. This prevents a complete match between the template and the target pattern. Sometimes a change in the size of the pupil reduces the correlation and the maximum correlation cannot be detected. In this method, there are some variations as to whether the density profile uses the full circle of the iris or only part of the circle. Merits and demerits of both methods have been discussed.[9]

In the present study, an iris pattern analysis of the full circle was done using video images obtained from the infrared CCD cameras built into the HMD. High-quality images of counter-roll torsional eye movement were recorded and a personal computer was used for accuracy analysis. There are few analysis systems that make image processing of torsional eye movement and real time measurement of torsional eye movement possible. These are very expensive. Our goal is to make it possible to analyze torsional eye movement by using a personal computer with free software, thus creating a low-cost system. Vergence eye movement and pupillary response of the HMD wearers can also be recorded. The present system will be useful for analyzing eye movements of HMD wearers who complain of motion sickness/VR sickness and also for clinical measurement of torsional eye movement.

Materials and Methods

Imaging and Recording System

Two sets of infrared CCD TV cameras, camera controllers, infrared illumination, and dichroic mirrors (reflect infrared, transmit visible light) were installed in a commercially available HMD (Glasstoron; Sony, Tokyo) modified by us to 3D display, as shown in Figure 1. The same parts as in a vertigo examination system[7] (ET110; Nihon Kohden, Tokyo) were used in this imaging system. The corneal reflectance of illumination can be reduced by a polarization filter. Motion blur of the eye can be suppressed by pulse light illumination synchronized with the TV cameras. A clear image is obtained. The headband of the HMD is detached, and the HMD is fixed to a

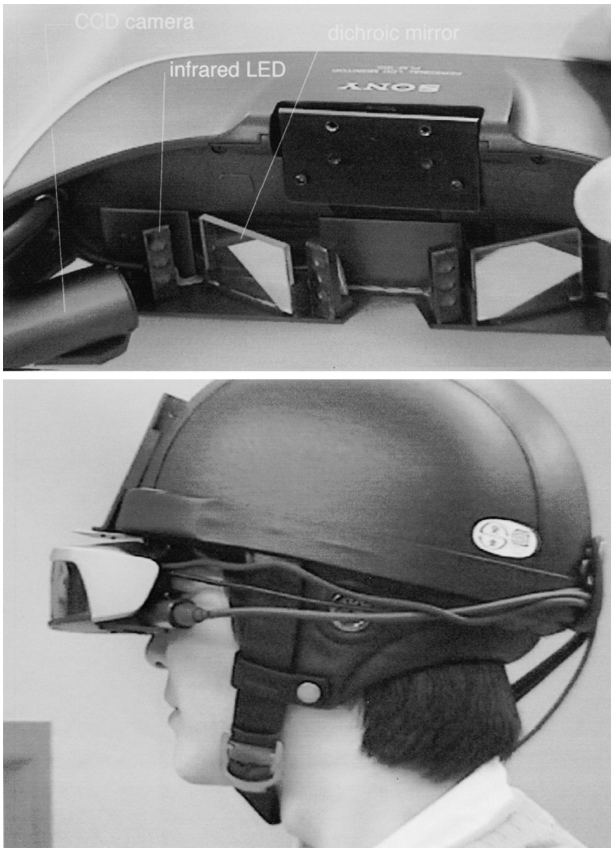

Figure 1. Upper: CCD camera set inside head-mounted display (HMD). Lower: HMD with new system worn by a subject. Third camera is not shown.

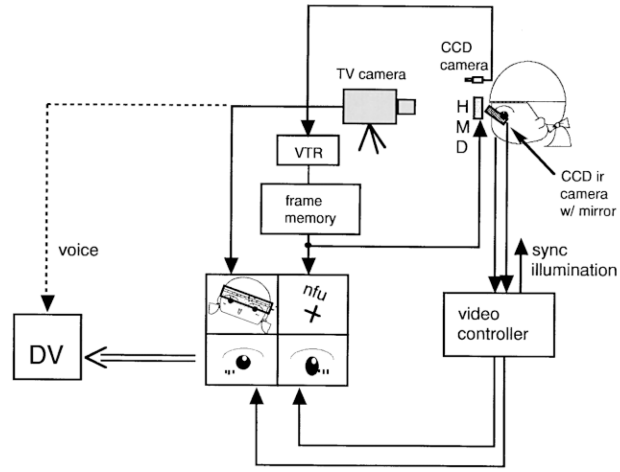

Figure 2. Schematic diagram of apparatus. DV: digital video, HMD: head-mounted display, ir: infrared.

helmet, with the position and angle of the HMD adjustable. In addition, the electric circuit of the HMD was modified, so that binocular parallax images can be presented. Therefore, presentation of HMD images of 2D and 3D and outside visual stimulus by the see-through mode were made possible.

Video images were stored in a digital video (DV) tape recorder (DHR-1000; Sony). DV stores image data in a series of frames (1/30 s images). Image capture was done with a DV interface board (MotoDV IEEE 1394; Radius, Mountain View, CA, USA) installed in a personal computer (PC; Power Macintosh G3MT/350; Apple Computer, Cupertino, CA, USA). QuadSwitcher equipment (YS-Q430; Sony), which synthesizes four images (image on the HMD [top right], image of monitoring subject's head motion [top left], and images in both eyes of the subject [bottom left and right]) on one frame was used. This composition is shown in Figure 2 and examples are shown in Figure 3 (visual stimuli of Figure 2 will be discussed later).

Software

Digitial video image capture is realized by the software included with the DV board (IEEE 1394 interface board). The captured movie is the standard QuickTime format with DV codec. This movie can be edited using utility software (QuickTime Player; Apple Computer) included in the system software (MacOS 8.6J; Apple Computer). This operation is the conventional "copy and paste." Then it is converted to the PICTs format file, and saved. The PICTs files can be analyzed using image analysis software (Public Domain Software "NIHImage ver 1.6" programmed by Wayne Rasband, National Institute of Health) and additional macro code. The result of the analysis is read by a conventional spreadsheet application. Calculation of the cross-correlation (mentioned below) is time-consuming in the macro execution. We attempted to speed this up by modifying the source code (Pascal language) in an additional unit ("User.p" in NIHImage). A commercially available programming tool (CodeWarrior Gold 10; Metrowerks, Montreal, Canada) was utilized in editing and compiling the source code.

The pulse illumination system used in our system is synchronized with the field signal of the CCD cameras. One-frame (1/30 s) image handled by the DV system is composed of two-field (1/60 s) images. If fast eye movement occurs, the two-field image seems to be motion blurred. The "de-interlace" macro command, distributed with NIHImage as one of the sample macros, was useful in such cases because it can separate two-field images.

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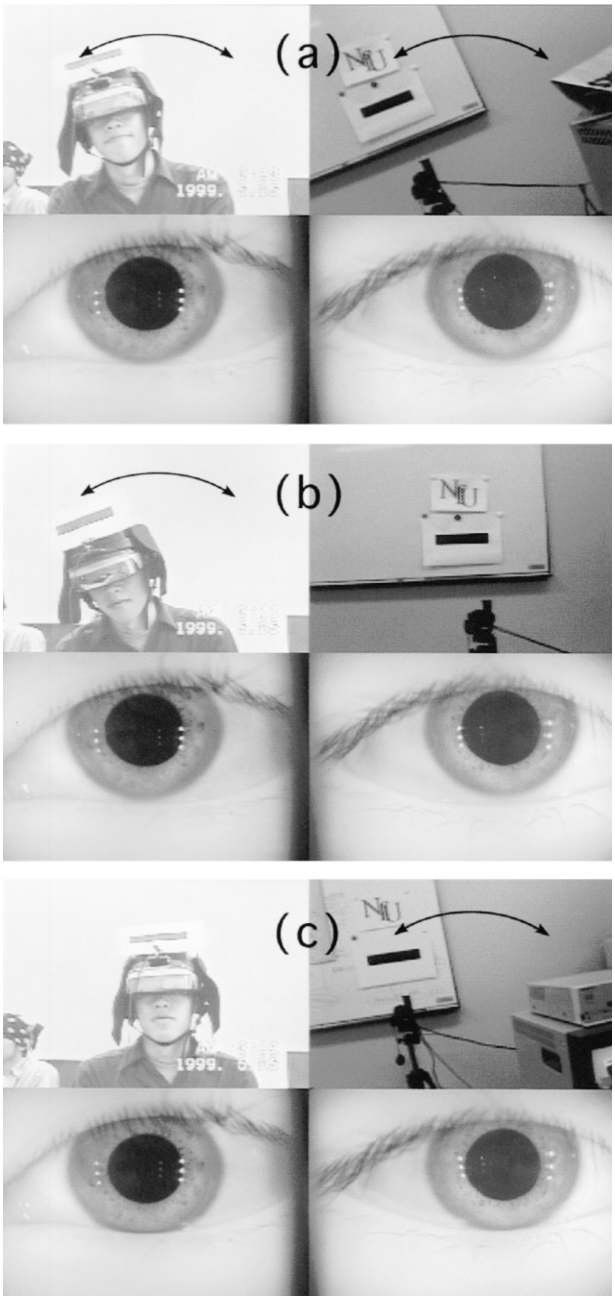

Figure 3. Head and image motion in three conditions. (a) See-through compatible mode, (b) head-mounted display (HMD) mode, (c) video mode. Third camera can be seen on HMD in each picture at top left.

Principle and Algorithm of Analysis

Iris pattern matching using the polar correlation method is based upon the method by Hatamian and Anderson.[8] Each human iris has a unique pattern that is formed by pigmentation and wrinkles. The direction from the pupil center does not change on this pattern, even if the size changes, or the eye moves. However, due to various reasons, such as illumination change or the distortion caused by changing camera angle, perfect matching is difficult, so maximum correlation is sought.

NIHImage creates a binary image first and then measures the center position and area of the pupil using the "Analyze Particle" command. By adjusting the threshold and particle size to be measured, the pupil alone can be detected. The diameter is calculated from the area and from an imaginary circle with a diameter slightly larger than the pupil. Density distribution is sampled on this circle in the fixed angle interval. Depending on the pupil size and interval of the angle, multiple sampling of the same pixels cannot be avoided but the correlation calculation is improved, unless the amount of multiple sampling is excessive. The coordinate system used in our analysis is that the angle is positive in a counterclockwise direction and that the zero-point is downward.

Generally, the number of calculation points gradually decreases in the cross-correlation function when the shift increases, unless the tails of the distribution drops to zero. However, in the polar cross correlation method of full circle that we used, the data is looped and the above-mentioned problem can be avoided.

A DV pixel is not square but rectangular and a DV image is composed of 720 (horizontal) $\times$ 480 (vertical) pixels, instead of the 640 $\times$ 480 size when the pixels are square. In our image analysis system, length (distance), position and area are encompassed by multiplying the coefficient.

Visual and Vestibular Stimuli

Torsional eye movement can be induced by the head roll motion (vestibular stimulus) and/or inplane rotation of the visual stimulus. The former corresponds to the VOR of head turn. This torsional eye movement is called counter-roll. The latter corresponds to the opto-kinetic nystagmus when the image motion is not rotational. The present experiment includes both stimuli. A subject wearing an HMD sits on a chair and shakes his head voluntarily from side to side to the rhythm of a metronome. The image projected on the HMD is taken by the third small TV camera fixed on the HMD and fed via frame memory and a VTR. A block diagram is shown in Figure 2. Thus, the image projected on the HMD moves in the opposite direction to the head. The subject can see the image fixed on the real space coordinate as the real object. This condition is called "see-through compatible mode," because this is compatible with the natural viewing condition without HMD. In this condition, both vestibular and visual stimuli are evoked without conflict. Once frame memory is switched on and the image of the HMD is frozen, visual stimulus is fixed even though a vestibular stimulus is being evoked. This condition is compatible with the conventional HMD view and is called HMD mode. The third condition is video mode in which the subject stops shaking his head and the images on the HMD is a replay of the recorded video scene in the first condition (see-through compatible mode). Only visual stimulus is present in this condition.

Head motion was also analyzed by the NIHImage. The tilt of the thick black line with white background attached on the head was analyzed by the "Analyze Particle" command. Simultaneous measurement of head and eye movements makes possible a detailed examination of the relation between these movements. The rotation angle of the visual image in the video mode was similarly analyzed.

Real-time Analysis of Binocular Eye Movement and Pupillary Response

Binocular eye movement and pupillary response are also measured by both image analysis and two real-time image processor boards (AZI-5510; Interface Corporation, Tokyo) installed into another PC (PC-9801 XA200; NEC, Tokyo). The image boards, one for each eye, create the binary images and feed the data of the center position and the size of the black part. Thus binocular eye movement and the pupillary response can be analyzed. The difference in binocular eye movement corresponding to vergence eye movement can be calculated. Analog output is also calculated by this PC via a D/A converter.

Examples of Measurements

Example of torsional eye movement during light reflex. Analysis of counter-roll torsional eye movement is shown during the voluntary head roll. Photic stimulation is provided by a flash of light during the measurement in order to show whether the present system works well with the change of pupil size.

First, the position and the size of the pupil are determined, and the density distribution of the iris pattern is profiled along the outside of the pupil. The profile is put on another image as one line (vertical line in Figure 4b). This procedure is carried out for each successive iris image. Figure 4b shows density change with time course in the abscissa and angular shift in the ordinate. Areas for which density deviates from the mean value over 2.5 SD should be considered artifacts so that the areas are filled by the mean density value. The vertical shift of the horizontal stripes of this image shows torsional eye movement. Two vertical lines, one of which should be the reference line, are used for cross correlation calculation. The shift where the correlation becomes maximum shows the amount of torsion. This calculation is repeated for all vertical lines.

In Figure 4a, the photic stimulus was provided by a flash of light during the measurement so that the pupil becomes constricted to half size. The calculated shift is superimposed in the right figure of Figure 4b as white dots (relative position in the vertical direction). Figure 5 shows calculated torsional, horizontal and vertical eye movements and pupillary reflex. During a 3-second period, a slow horizontal eye movement (VOR) of 10° can be observed. Changes in pupil diameter do not affect the calculation of torsional eye movements. Resolution of the torsional eye movement is 0.2° and the sampling rate is 60 Hz.

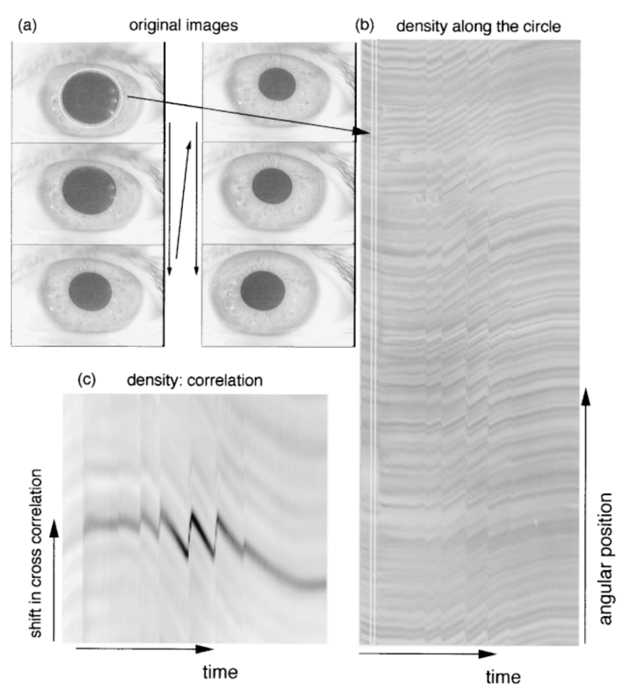

Figure 4. Analysis of iris pattern. (a) Original movie. Pupil constriction by light stimulus started at around the third photo. Density distribution along circle just outside pupil (a) is reprojected to one line per image onto another image (b). (b) Torsional eye movement can be read from change in vertical position of horizontal stripes. (c) Cross-correlation function as density with changes in time, and shift between reference and test iris pattern.

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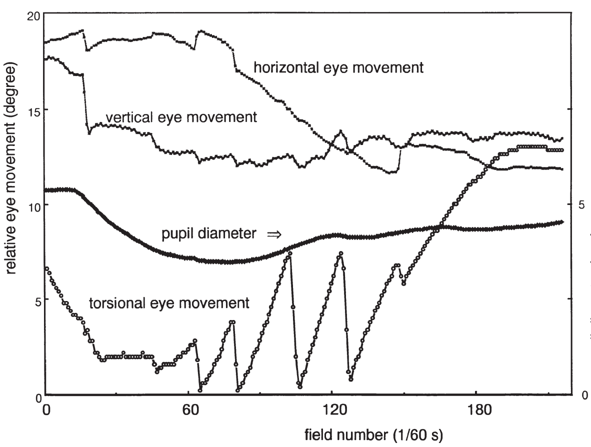

Figure 5. Example of analysis obtained from Figure 4.

Example of simultaneous measurement of head roll and torsional eye movement. The present analysis method was applied to a quadrisectional image as shown in Figure 3. A subject moves his head voluntarily during a constant period (2 seconds) following a metronome. Resolution of the analysis is 0.5°. The result is shown in Figure 6. Figure 6a indicates the results of analysis in the see-through compatible mode. Head motion is close to a sinusoidal curve. Amplitude of the counter-roll eye movement is smaller than head motion. Velocity gain of the counter-roll torsion to the head roll is approximately 0.47. Figure 6b shows the result of HMD mode. The result is similar to Figure 6a. Velocity gain is about 0.45. Figure 6c shows the result of video mode. Small torsional eye movement is induced in this condition. Torsion induced by the rotating image should be in the same direction as the image rotation. Upper right picture of Figure 3 is the view from the subject, while other pictures are the views from outside the subject. Thus eye movement and image rotation seem to be in opposite directions in Figure 6c.

The results show that there is no visual suppression in counter-roll torsional eye movement in this subject. Using 5 more subjects, the averaged gain of visually suppressed counter-roll torsional eye movement was approximately 70% compared to the gain of the see-through compatible mode. This is in contrast to the yaw-induced VOR where visual suppression is almost complete. Details of this experiment will be published in a future report. With head placed eccentrically from the axis of roll motion, as in the present study, otolith-mediated linear VOR (LVOR) components interacted with the canal-mediated angular VOR (AVOR) to yield a combined AVOR-LVOR

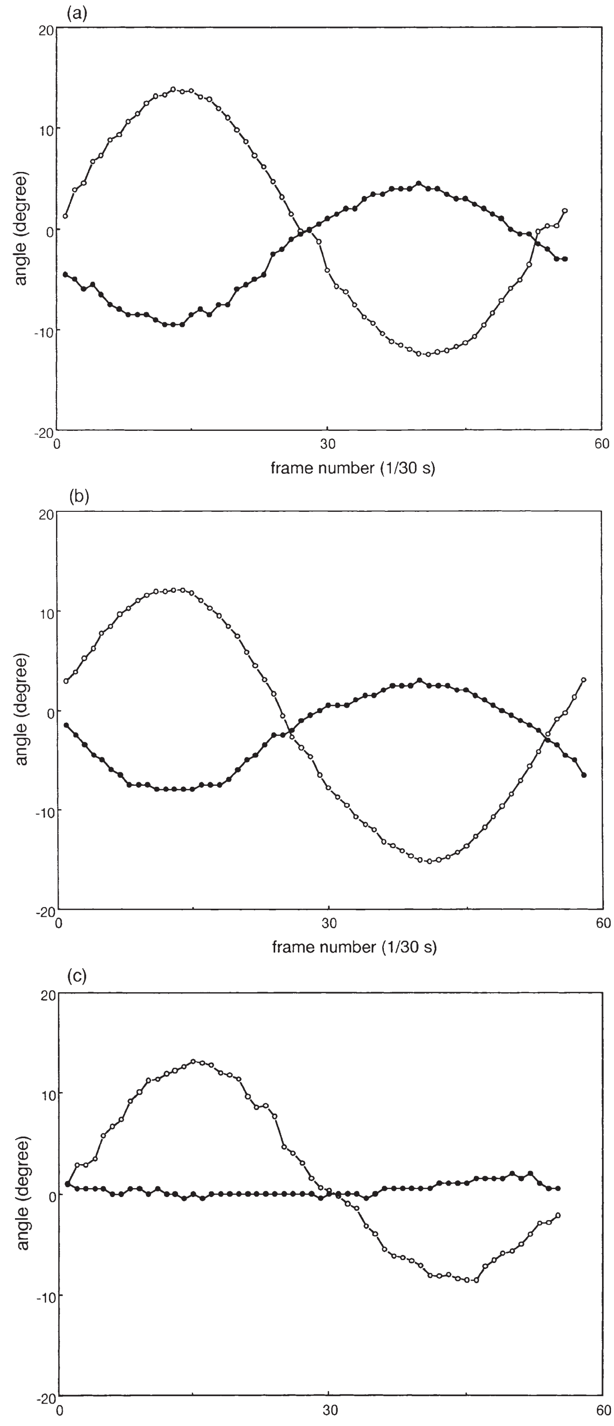

Figure 6. Calculated torsional eye movements and head roll movement. (a) See-through compatible mode, (b) head-mounted display mode, (c) video mode. o—o—o—o: head roll in (a) and (b) and image rotation in (c); •—•—•—•: torsional eye movement.

response.[10] We have to consider that this effect is included in the results of the present study.

Discussion

To obtain a clear iris image is most important for the analysis method of iris pattern tracking. Our new system can reduce the reflected image of infrared illumination by a polarizing filter, and the motion blur by synchronized illumination with the TV camera. Our system improved the image quality. The DV was useful for recording the clear image; it was also effective in reducing the cost of the operation of capturing the image. The system of image analysis is usually expensive, and a long time is required for the construction of the system. A practical operation plan made it possible to construct the systems in a few days and make it sufficiently useful by utilizing free software with advanced functions.

Some problems are recognized in torsional eye movement measurement by iris pattern.[11,12] For example, since the eyeball surface has a curvature, the image obtained also has a curvature due to the general properties of the camera lens. So the image is deformed when the pupil is not at the center. The polar correlation method is also affected by this image deformation. However, some problems caused by this defect are resolved using the full circle polar correlation method. The upper part of the pupil is sometimes covered by the upper eyelid, especially when the eye moves upward or inward from center. In this case, it is better to track the lower part of the iris pattern.[11] Due to this problem, the full circle method is described as "not practical."[9] The present work revealed that deviation in the position of the eye up to 10° horizontally and 5° vertically cannot affect the torsional analysis in many subjects. Thus the full circle polar correlation method is useful unless a large deviation of the eye is predicted (e.g., nystagmus examination in otorhinolaryngology clinics).

The minimum interval of angular sampling is 0.2°. The shift in the cross-correlation and resolution of calculated torsional eye movement is also 0.2°. The results show a smooth continuation. Actually 1,800 sampling points around the pupil are selected. Pupil diameter, which varies from time to time, is assumed to be about 200 pixels vertical, and the circle around the pupil consists of approximately 600 pixels. Each pixel is sampled about three times on average. Clearly this is over-sampling. However, when actual measurement results obtained by 0.2°, 0.3°, and 0.4° intervals are compared, the accuracy seems to be improved as the interval becomes smaller. In contrast, when the image is divided into four parts as shown in Figure 3, the limit of resolution was approximately 0.5°.

Torsional and vergence eye movement and pupil movement of the HMD wearer has been difficult to measure but our cameras this possible because they are built into the HMD. Especially in an analysis of VR sickness, if an HMD is used as a display for VR, our equipment will be essential. Analysis of the torsional eye movement was difficult until now. With our equipment, the image analysis could be carried out easily, because the image quality of the system is sufficiently high. The measurement of the torsional eye movement in ophthalmology and otorhinolaryngology clinics is also important, and our equipment and analysis methods are also applicable in these fields. Reports have already been published[13,14] using our device for measuring involuntary torsional eye movements to clarify the efficiency of surgery in a patient with myokymia of the superior oblique muscle.

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