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Inexpensive system for real-time 3-dimensional video-oculography using a fluorescent marker array

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Abstract

We describe a novel, inexpensive method for real-time measurement of binocular three-dimensional eye position. The method employs consumer-grade digital video cameras ("webcams") to track an array of three fluorescent non-collinear markers affixed to each eye. The instantaneous position of the marker array relative to a reference position is used to construct a rotation matrix describing the eye rotation. The mathematical computation used to determine the rotation matrix is conceptually simpler and computationally more efficient than methods previously described, allowing generation of binocular three-dimensional eye position in real-time during image acquisition. The fluorescent marker is illuminated using a UV-A light source. The light source and reflective artifacts are filtered out to improve the signal to noise ratio. In addition, we present a method to align the camera with the center of eye rotation. When tested in vitro, the video-oculography (VOG) method had a <2.9% positional error (in each component of 3-D eye position) for eye positions within 20° of center. We directly compared this method of VOG to the search coil technique by measuring three-dimensional eye position simultaneously using search coils and VOG in a chinchilla (*C. laniger*). The in vivo positional difference between the two methods was <3.1% for each component of 3-D eye position.

Keywords: Three-dimensional; 3-D; Video-oculography; Eye position; UV; Fluorescent; Vestibular; Vestibulo-ocular reflex; VOR

1. Introduction

Precise and accurate measurement of eye rotation is central to vestibulo-ocular research. The eye can rotate in three dimensions: horizontally, vertically and torsionally (about the line of sight). The "gold standard" method for measuring three-dimensional eye position is the scleral search coil technique (Robinson, 1963; Collewijn et al., 1985). In animal experiments, the search coils can either be implanted (Paige and Tomko, 1991; Minor et al., 1999) or glued to the eye (Gilchrist et al., 1998). Implantation of search coils can restrict eye movements due to conjunctival scarring and inflammation or coil lead tension. These problems become increasingly significant when coils are implanted in rodents and other species with small eyes (Stahl et al., 2000). Depending on surgical technique, coil implantation can also damage extraocular muscles and their pulleys, further distorting eye movements (Demer et al., 1995). Temporarily gluing coils to the frontal surface of the eye minimizes the risk of restriction due to scarring; however, glued coils and their leads can impede eye movement range by impacting the lids and canthi. Repeated impact of the coils against lid margins can dislodge the coils, limiting the duration of experiments. Whether implanted or glued, search coils require uniform, stable magnetic fields for transduction of eye rotation. These fields can

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be distorted by metallic objects and by currents flowing in equipment nearby.

The drawbacks of the search coil technique have prompted efforts to develop video-oculographic (VOG) systems for measurement of three-dimensional eye position. Such systems are gaining wider acceptance. Horizontal and vertical eye position can be determined by tracking the pupil and/or a corneal reflection (Stahl et al., 2000; Kaufman, 2002). To determine ocular torsion, most currently available VOG systems either track two or more landmarks on the eye, which involve the use of vector cross products to calculate the axis of rotation (Nakayama, 1974; Parker et al., 1985; Yamanobe et al., 1990; Ott et al., 1990), or employ some variation of the polar cross correlation method, which involves measuring and tracking changes in iral contrast along a circular sampling path (Anderson and Hatamian, 1983; Vieville and Masse, 1987; Clarke et al., 1991; Moore et al., 1991). In humans, pronounced iral striations make the polar cross correlation method practical. In animals that do not have pronounced iral striations, such as the chinchilla, rabbit, guinea pig and mouse, it is more practical to track attached landmarks.

We describe an inexpensive technique for real-time measurement of three-dimensional eye position using consumer-grade digital video cameras to track an array of three 1 mm × 1 mm markers on a piece of plastic film affixed to the cornea. To increase contrast between the markers and unwanted corneal reflections, the markers were fluorescent and illuminated with a UV-A light source outside the camera's range of spectral sensitivity. The marker array was glued to the frontal surface of each cornea and typically remained attached for >4 h. The three-dimensional eye rotation necessary to move a marker array from a reference position to a final position was calculated using a mathematical method that is simpler and more efficient than others described in the literature (Nakayama, 1974; Ott et al., 1990). We used inexpensive, consumer-grade "webcam" digital video cameras with modified lenses and the LabVIEW G programming language (National Instruments, Austin, TX) to simplify software development. Binocular three-dimensional eye positions were computed and displayed in real-time using an intuitive graphical user interface. We validated the system in vitro using a Fick gimbal and in vivo by comparing eye movement measurements made simultaneously using both search coils and VOG.

2. Materials and methods

2.1. Fluorescent marker array and light source

We fabricated fluorescent marker arrays using plastic film laminated on paper saturated with fluorescent yellow ink. The film was opaque except for three transparent 1 mm × 1 mm windows separated by 1 mm and arranged in a 45° right triangle. (This pattern was formed using a Casio KL-750 film-based label maker to print a colon followed by a period [:.]. The distance between the windows of the plastic ink backing tape was fixed at 1 mm.) A small amount of cyanoacrylate was used to improve adhesion of the marker array to the eye, as used in previous animal studies (Hess and Dieringer, 1991). In order to measure vestibular-mediated eye movements in the absence of vision, we deliberately covered the pupil with a thin film of cyanoacrylate. For experiments requiring intact vision, the marker array could be placed away from the pupil, or on an annular contact lens. A diffuse ultraviolet (UV-A) light source (360 nm peak, 9 W, FPX7BLB, Ushio Inc., Japan) illuminated the array (Fig. 1). Alternatively, 380 nm UV-A light-emitting diodes (LEDs) (SSL-LX5093SUVC, Lumex Inc.) are also suitable. Depending on the spectral sensitivity of the specific camera used, a UV cut filter (SKYLIGHT 1B Hoya, Japan) or a yellow pass filter (K2 yellow filter Hoya, Japan) can be used to improve contrast. No filter was necessary with the webcams we used, because their color CCD is already less sensitive to UV than most monochrome image sensors.

Fig. 1. Fluorescent marker array on the eye of a chinchilla. For this photograph, the eye was illuminated with visible light in addition to UV. Under normal testing conditions, only UV illumination is used, increasing the relative brightness of fluorescent markers.

The maximum allowable exposure of UV-A (320–400 nm) that will not harm the eye (cornea and lens) for human use is 1 J/cm^2 (ICNIRP, 1996). The "black light" or UV-A lamp (sometimes called a "Wood's Lamp") that was used in this study is not considered hazardous because the UV-A radiance at the *lamp surface* is only about 3 mW/cm^2. At 30 cm distance, the UV-A radiance at the *eye surface* is about 50 μW/cm^2 and would require >5 h exposure to reach 1 J/cm^2. The UV LED light source generates about 3 mW, the beam angle is 30° so at 20 cm, the UV-A radiance at the *eye surface* is about 33 μW/cm^2 and would require >8 h to reach 1 J/cm^2.