A method for measuring eye movements using Hall-effect devices

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A system for precise recording of eye position and movements in laboratory animals, by means of Hall-effect devices, is described. The system, useful in neurophysiological and neurobehavioral studies, allows the analysis of saccadic eye movements, optokinetic- and vestibular-induced nystagmus, slow tracking movements, eye vergences, and so forth. This small, light-weight, and inexpensive system uses a set of Hall-effect devices and associated electronics to sense variations in the position of high-power magnets fixed in the eye sclera or in scleral contact lenses. The output of the Hall-effect devices is amplified by operational amplifiers, collected through an A/D converter, and analyzed in a PC computer by specific software.

The systems for tracking eye movements and positions have a wide application in different research and clinical areas, such as neurophysiology, psychobiology, or clinical and experimental neurology. A number of different methods for measuring eye movements have been developed to date, such as electro-oculography (Watanabe & Takeda, 1996; Young & Sheena, 1975a), the search coil technique (Robinson, 1963; Schlag, Merker, & Schlag-Rey, 1983), infrared light corneal or scleral reflecting systems (Bach, Bouis, & Fischer, 1983; Eizenman, Frecker, & Hallett, 1984; Reulen et al., 1988; Young & Sheena, 1975b), video-oculography (Discenna, Das, Zivotofsky, Seidman, & Leigh, 1995; Ott, Gehle, & Eckmiller, 1990), and laser-ophthalmoscopy (Ott & Lades, 1990; Ott, Lades, Holthoff, & Eckmiller, 1990). Each of these techniques presents advantages, limitations, and inconveniences. Thus, among the most widespread methods, electro-oculography presents the advantage of easy application and lower cost, but also limitations of bandwidth, low stability, and contamination by nonocular events. The search coil technique presents long-term stability and high resolution but some inconveniences, such as the difficult ocular coil implantation, the presence of wire leads, the interference of alternating magnetic fields on the simultaneous recording of other neurophysiological variables, and high cost.

The present paper describes an inexpensive system using Hall-effect sensors for precisely measuring the horizontal and vertical components of eye movements such as saccades, optokinetic- and vestibular-induced nystagmus, slow tracking movements, eye vergence, and so forth.

The Hall effect consists in the generation of a voltage across an electrical conductor carrying current when it is placed in a magnetic field. Thus, the Hall-effect sensors produce an output voltage that changes in proportion to the intensity of the surrounding magnetic field. In the present application the magnetic field is provided by a small magnet attached to the eye sclera. The system described here has some advantages over existing tracking methods, because it provides a degree of precision, resolution, and dynamic range similar to the most precise and widely used methods, but is small, light weight, and technically simple. In addition, this system allows the recording of eye movements during simultaneous recording of brain activity or brain stimulation, given that it is immune to, and does not produce, electric interference with other electrophysiological recording or stimulation equipment.

METHOD

The system for recording eye movements consists of a set of Hall-effect transducers positioned in orthogonal planes around the orbit, to record the horizontal and vertical components of the movements of one or both eyes by measuring the intensity of the magnetic field generated by miniature magnets fixed on the sclera. The analog output of the sensors is amplified and collected by an A/D converter to be displayed on line in a PC computer, and stored for posterior analysis.

The Sensors and Magnets

This eye movement recording system consists of an integrated circuit based on high-sensitivity Hall-effect sensors (i.e., Honeywell or Siemens devices). In addition, this design includes a temperature-compensating amplifier, a voltage regulator, and an output transistor. Laser trimmed thick film resistors result in consistent sensitivity from one device to the next and provide compensation for temperature variations. These analog devices produce

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Figure 1. View of the Hall-effect sensor-based eye movement recording system ready to record in a goldfish. (a) Hall-effect sensors and sockets; (b) positioning arm; (c) stand; (d) output and power supply connectors; (e) magnet; (f) water supply device; (g) fish holder.

an output voltage proportional to the intensity of the magnetic field to which they are exposed, and thus, proportional to the distance between the magnet and the sensor.

The magnets, affixed to the sclera of the eye, provide the constant magnetic field to measure the eye movements and position. In the present work, small, powerful, pressed rare earth magnets were used, but other magnets or fragments of magnetic materials of the desired weight and size can also be useful. To test the suitability of the Hall-effect device to record eye movements in goldfish we used 25-mg and $2 \times 2 \times 1$ mm (width $\times$ height $\times$ depth) magnets. These were affixed to the eye sclera directly by means of surgical sutures or cyanocrylate surgical adhesive, although they could be incorporated in scleral lenses.

The Sensor Positioning Procedure

The sensor positioning system is shown in Figure 1. The Hall-effect transducers are positioned by means of an arm supported by a steady stand that facilitates the precise adjustment of the sensors around the orbit. The Hall-effect sensors are inserted in two sockets glued in orthogonal planes to the end of the arm, which allows them to be replaced rapidly if necessary. The vertically oriented sensor provides the horizontal eye movement component, whereas the horizontally oriented transducer provides the vertical component. A plastic case covers the positioning arm and the sensor connection wires. The final position of the sensor with respect to the magnet is that in which any change in eye position within the oculomotor range is monitored by a shift in dc output voltage. For the present experiment, the sensor was at a distance of 3 mm from the magnet when the eye was in the center of the orbit. It should be noted that a positioning arm could

be fixed to the cranial bones directly, by means of stainless steel screws and dental cement. The latter possibility is most convenient when simultaneous electrophysiological recording or stimulation is required. In this case, the arm could be fixed to the same headplug that is used for electrodes and connectors.

After the sensors were adequately positioned, the calibration procedure was carried out by turning the eye ball at known angles, pushing it by means of a needle driven by a micromanipulator, and simultaneously recording the dc voltage output of the sensor. Since the oculomotor range of goldfish is $\pm 15^\circ$, the calibration procedure consisted in turning the eye at angles of $\pm 2.5^\circ$, $\pm 5^\circ$, $\pm 7.5^\circ$, $\pm 10^\circ$, $\pm 12.5^\circ$, and $\pm 15^\circ$ under a surgical microscope. Within this oculomotor range, the output of the system was broadly linear. Nevertheless the correction of nonlinearities of the system was solved by using the method described elsewhere by Nienhuis and Siegel (1989). This method consisted in creating a continuous function from the dc output voltages of the sensor for each eye angle calibration with the use of the Newton's interpolating polynomial. This procedure allows the conversion of any recorded voltage output of the sensors into the corresponding angles of the eye turns. This method also permits the precise recording of eye movements in animals with greater oculomotor ranges.

Signal Amplification and Data Collection

The analog voltage output signals from the sensors for the horizontal and vertical eye movement components were amplified by operational amplifiers and collected and stored on a PC computer with an A/D converter.

Operational amplifiers with offset and variable gain were used. The schematic of the amplifier circuit for the output of the Hall-effect device is shown in Figure 2. The first operational amplifier (IC LM 301) provided an offset adjust that was used to zero the initial voltage output of the Hall-effect sensors. The next step was an amplifier circuit with variable gain, using two operational amplifiers (IC LF 355). The balance control and gain adjustments allowed adjustment of the sensor voltage output to the voltage range required by the A/D converter and provided compensation for variations due to animal dimensions or mounting differences. Alternatively, a commercial, standard dc amplifier with offset adjustment and variable gain could be used. To power the Hall-effect sensors and the amplifiers, a stabilized constant-current source providing a voltage between ± 7 and ± 12 V was used. A battery that supplied a voltage ranking between these values could also be used. An A/D converter card and a PC computer were used to collect the analog input from the sensor's amplifier. The system collected the data from the horizontal and vertical components of the movements of one or both eyes. In addition, the output signal from the sensor amplifiers could be directly monitored by an oscilloscope or polygraph and stored in a commercial multichannel magnetic recorder.

Figure 2. Schematics of the amplifier (A) and the power supply (B).

RESULTS AND DISCUSSION

Illustrative examples of spontaneous and induced eye movements recorded by the Hall-effect measuring system in goldfish are shown in Figure 3. This system is able to record eye position and movements within a wide oculomotor range (for the case of goldfish, about 30°). Furthermore, the time course of movements and their velocity profiles show the features of the eye displacements recorded by other methodologies in both goldfish (Salas, Herrero, Rodríguez, & Torres, 1997; Salas, Navarro, Torres, & Delgado-García, 1992) and other vertebrates (Fuchs, 1967). Thus, the amplitude versus velocity and amplitude versus duration relationships showed logarithmic and linear adjusts, respectively (Figure 4), and these relationships show the same characteristics in gain and shape as those previously reported in goldfish (Salas et al., 1997; Salas et al., 1992) and other vertebrates, including humans (Fuchs, 1967), using the search coil technique. In addition, the records were stable, as was indicated by both the trace during the ocular fixation (Figure 3A), and the center of the oculomotor range, obtained as the middle of the eye position after 15 min of recording, did not drift over the experimental session (duration of sessions,

3–6 h); the gain of eye movements during vestibular and optokinetic stimulations was as that reported previously (Keng & Anastasio, 1997; Salas et al., 1992) and was irrespective of turn direction (Figures 3B–3C). Eye vergences and vertical displacements do not appear spontaneously in restrained goldfish, but when they were produced by electrical stimulation of the optic tectum, the data for these movements were similar to those described elsewhere (Figure 3D; Salas et al., 1997). All these data together show that the relative weight and size of the magnet with respect to eye characteristics (the eyeball was 650 ± 50 mg, and its diameter was 9 ± 1 mm for goldfish of length 20 cm) was not a restraint upon performing precise recording of eye movements in laboratory animals like goldfish.

The system for measuring eye movements using Hall-effect transducers described here has shown a remarkably high sensitivity and reliability in the different situations in which it has been tested in our laboratory. This system expands upon previously reported applications of the Hall-effect devices for ambulation measurement (Arms et al., 1984; Bramanti & Tozzi, 1990), accelerometers (Korhonen, 1991), and head (Nienhuis & Siegel, 1989), eyelid (Hamiel, Bleicher, Tubach, & Cronan, 1995; Hamiel,

A. SPONTANEOUS

B. VESTIBULAR

C. OPTOKINETIC

D. ELECTRICAL

Figure 3. Illustrative examples of eye movement records using the Hall-effect system in goldfish. (A) Spontaneous eye movements recorded over 30 sec (left); some examples of these movements at a different time scale (right). Filled and empty triangles show different sizes of saccadic eye movements corresponding to different velocities of displacement in both nasal and temporal directions; star shows the trace of eye position during a fixation. (B) At left are shown vestibularly induced eye movements (above), and hand rotating the animals at 0.1 Hz (below); at right, a detail of the time course of eye position during a hand-induced vestibular nystagmus. (C) Optokinetic eye movements evoked by turning the whole visual field either clockwise or counterclockwise at a velocity step of 18°/sec (left); a detail of the time course of eye position during an optokinetically induced nystagmus (right). The dotted line indicates the onset of the direction change. (D) Electrically induced eye movements following focal stimulation within the optic tectum. At left, effects of increasing the stimulus current strength on the size and velocity of eye movement. Middle, a convergent eye movement. Right, two examples of saccadic movements with different horizontal and vertical component amplitudes. Eh, Ev, horizontal and vertical components of eye position; $\dot{E}h$, trace velocity of the horizontal component of eye movement; Eh0, Ev0, central position in the orbit of the horizontal and vertical components of the eye; $\dot{E}h0$, zero position of $\dot{E}h$; H, head position; L, rotation of the animals toward left; QP, SP, quick and slow phases of nystagmus; st, stimulus onset; T, temporalward direction of eye movement.

Figure 4. Peak velocity (A) and duration (B) of horizontal spontaneous saccades against amplitude. Each point is the average of 20 recorded spontaneous movements for a representative goldfish; the bars represent standard deviations of the mean.

Tubach, Bleicher, & Cronan, 1994), tooth (Yamada, Yoshida, Kobayashi, & Yamauchi, 1990), and jaw (Deich, Houben, Allan, & Zeigler, 1985) movement recording.

In summary, the system described here allows the precise recording of eye movements in laboratory animals; it offers sufficient resolution, linearity, and dynamic range. Other remarkable features of this Hall-effect-based system are the recording stability during long time periods, the low interference with normal vision, the high amplitude of the output signal provided by the sensors, the immunity to electromagnetic interferences generated by other laboratory systems or to variations in the illumination conditions, and the fact that the system is not a source of electromagnetic interferences for other highly sensitive recording devices used simultaneously. In addition, the system presents considerable technical simplicity and low cost, which permits the use of various units in the same laboratory. All these features make this system remarkably useful for investigations of the behavioral and neural mechanisms underlying eye movements, in situations in which the precise recording of eye movements and position is required.

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