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A SOFT CONTACT LENS SEARCH COIL FOR MEASURING EYE MOVEMENTS

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Abstract—A five turn coil of magnet wire sandwiched between two soft contact lenses served as a magnetic search coil to measure horizontal and vertical eye movements in humans. The lens was adhered to the eye for 35 min by periodically misting the eye with distilled water; during this time the records of eye position showed that the lens remained firmly attached to the eye. Using this sensor, no topical anesthetic need be applied and the lens can be worn for an extended period of time without increasing intraocular pressure.

Soft contact lens   Magnetic search coil   Eye movements   Instrumentation

INTRODUCTION

The magnetic search coil method of recording eye movements was first described by Robinson (1963). In his original system, a coil of magnet wire is embedded in a hard contact lens and struck to the eye by evacuating the chamber between the lens and the cornea. When the coil is placed in a time-varying magnetic field a voltage is induced in the coil. This voltage is amplified and the subsequent phase detection results in a signal proportional to the sine of the angular position of the eye in space. Horizontal, vertical and torsional eye movements can be simultaneously recorded using two coils—one for horizontal and vertical, and the other for torsional movements.

Widespread use of this system was hampered by the need to evacuate the hard contact lens on the eye. Such evacuated systems can cause corneal deformation, corneal abrasions, increased intra-ocular pressure, and discomfort to the subject. Collewijn *et al.* (1975) removed the need for a hard evacuated contact lens by embedding the magnetic coil in a specially molded silicone rubber ring that could be adhered to the eye by suction when the ring is pressed on to the scleral portion of the eye. This improvement expanded the application of the magnetic search coil method in the laboratory and in the clinic.

Despite the vast improvement of the silicone rubber ring over the evacuated hard lens, it was still necessary to anesthetize the eye. Furthermore, the intraocular pressure rose from 12 to 20 mmHg over the time the silicone rubber ring was worn (Collewijn *et al.*, 1975). A further improvement in the search coil system was the elimination of the lead wires from the search coil (Reulen and Bakker, 1982 for details); these wires have proved to be a source of eye irritation for some users (Robinson, 1981). However, even the leadless sensor still required the use of a corneal anesthetic prior to applying the sensor to the eye.

This report describes a further improvement in the magnetic search coil system: The search coils are sandwiched between two soft contact lenses and then adhered to the eye with distilled water, as suggested by Edelman (1979).* Such a sensor can be used to measure horizontal, vertical and torsional eye movements under conditions where the possibility of increased intra-ocular pressure and corneal abrasions from a coil sensor prohibits the use of currently available magnetic coil sensors. One such environment is in a space-based laboratory where the inaccessibility of subjects in this environment requires severe restrictions on the instrumentation that can be used for physiological measurements. The soft lens search coil sensor (soft-coil for short) eliminates the need for a corneal anesthetic and the side effect of increased intraocular pressure.

Thus far, in tests on three subjects, none of whom are contact lens wearers, the soft lens sensor has been used without problems or discomfort. Furthermore this sensor is inexpensive and simple to construct. A single pair of soft contact lenses has been used for as long as a year and used to make several search coil sensors.

METHODS

A magnetic search coil was formed by winding five turns of number 44 (0.1 mm dia) polynylon insulated copper magnet wire to a diameter of 10 mm

*Adhesion of soft lenses to the eye, described by Chen and Cyr (1970), was first used as a tool for aiding the measurement of eye movements by Edelman (1979) and Edelman *et al.* (1981). They applied this observation to adhering landmarks on a soft contact lens to the eye to aid in the measurement of torsion using a video camera.

(Robinson, 1963). The two lead wires were then twisted as they left the coil to reduce magnetic interference. The coil had a d.c. resistance of 7 ohms and a thickness of approximately 0.5 mm in diameter when sandwiched between the lenses. The total thickness of the search coil lens was about 0.7 mm.

The soft lens search coil was constructed by placing the coil of wire between two ordinary 13 mm diameter Bausch & Lomb soft contact lenses (B&L Plano B4). Both lenses sat in distilled water 30 min prior to construction of the sandwich. First, the bottom lens of the sandwich was placed on a soft lens holder from a B&L lens case. The lens was allowed to dry until its surface was tacky, about 5 min depending on temperature and humidity conditions. Then the coil was placed on the front surface of this lens and the second lens, which was also allowed to dry till tacky, was placed over the coil and the first lens. Finally, the two lenses were pressed together to remove any trapped air and to form a tight seal around the coil. When done properly, the coil is encased between the lenses*. Finally, the front surface of the lens sandwich was irrigated with distilled water and allowed to dry, approximately 10 min, then rehydrated in saline for 3 min before being worn.

At the beginning of the experiment, the soft lens search coil was placed on the eye and irrigated with distilled water to adhere it to the eye (tap water can be used if the salt content is low enough). After 3–4 applications of distilled water (removing the excess water with a paper towel), the lens adhered to the eye (many times an individual can feel a light pressure as the lens tightens on the eye). Before and after the experiment a subjective test of lens adhesion was performed by pushing lightly on the lens with a finger. If the lens was stuck to the eye, the lens and the eye were observed to rotate together. The subject was then placed in the magnetic field with head movements restrained by a full mouth bite bar fitted to the subject. At 20 cm from the subject's eye was placed a matrix of crosses used as fixation points during the experiment. The crosses were separated by $\pm 2^\circ$, 5°, 10° and 15° from the central fixation point and were oriented horizontally, vertically and obliquely (45°). During the experiment the subject first fixated the central cross for 10–20 sec, followed by 40–60 sec of saccadic eye movements to the crosses on the calibration matrix. There was no set pattern to these saccadic movements only that they should be made in quick succession so that a large number of eye movements occurred during the intervals between steady fixation on the central cross. Horizontal, vertical and oblique eye movements were performed along with normal and rapid blinking so as to stress the adhesion of the lens to the eye.

*Attempts to separate the two lenses at this point usually result in torn lenses. If the lens is allowed to sit in saline for 2–4 weeks, the two lenses can be gently separated from each other without damage to the lenses.

The testing lasted for 15 min; however, the total time of adhesion was 35 min which included setup and calibrations. The results from unpublished experiments using a single soft contact lens on 20 subjects have indicated that once adhered to the eye, a soft contact lens will remain stuck to the eye for 3–6 min if no more distilled water is applied. To keep the search coil lens adhered for an extended time the lens sandwich was sprayed approximately every two minutes with distilled water (approximately 1 ml per spraying) using an ordinary perfume atomizer (Oman, 1981; personal communication). This procedure had little effect on the conduct of the experiment.

The twisted pair of wires from the search coil were connected to a magnetic coil system which had a noise level of 0.1° and bandwidth of 300 Hz (Remmel, (1984). Horizontal and vertical eye movements were sampled at 1000 Hz using a PDP 11/34 computer. The raw eye position was displayed using a graphics system with cursor controls so that saccadic amplitude and duration could be measured. Eye position was differentiated to obtain velocities using a 5 point difference algorithm that had a bandwidth of 200 Hz (Bahill *et al.*, 1981). Main-sequence plots were constructed from pure horizontal movements from one subject.

RESULTS

The sensor remained stationary on the eye throughout the course of the experiments. The eye movement records in Fig. 1(a) attest to the stability possible using the contact lens sandwich and distilled water. The record in Fig. 1(a) shows a subject fixating on the center calibration cross followed by a series of saccadic eye movements. This pattern of fixation and saccades is repeated throughout the experiment. These recordings show that within our noise level the fixation base-line remains stable between saccadic interludes and even after the series of blinks shown in Fig. 1(b). Comparison of the baseline in Fig. 1(a) at the start of the experiment to those taken at the end of the experiment, Fig. 1(b), shows the stability in the horizontal and vertical fixation baselines.

Another experiment, using a different soft search coil lens, on a different day, on the same subject, showed that the lens adhered to the eye as well as in the previous experiment. To date, three subjects have used the soft contact sensor with comparable results.

To establish lens stability and identify changes in the fixation baseline, the instrument's gain was high, thus some of the saccades performed between fixations saturated the computer's recording system. However, many saccades were analyzable especially those below 15°. The peak velocities and durations of the horizontal saccades recorded during these experiments, Fig. 2, are within the range of values expected from a normal individual (Bahill *et al.*, 1981; Abel *et al.*, 1983).

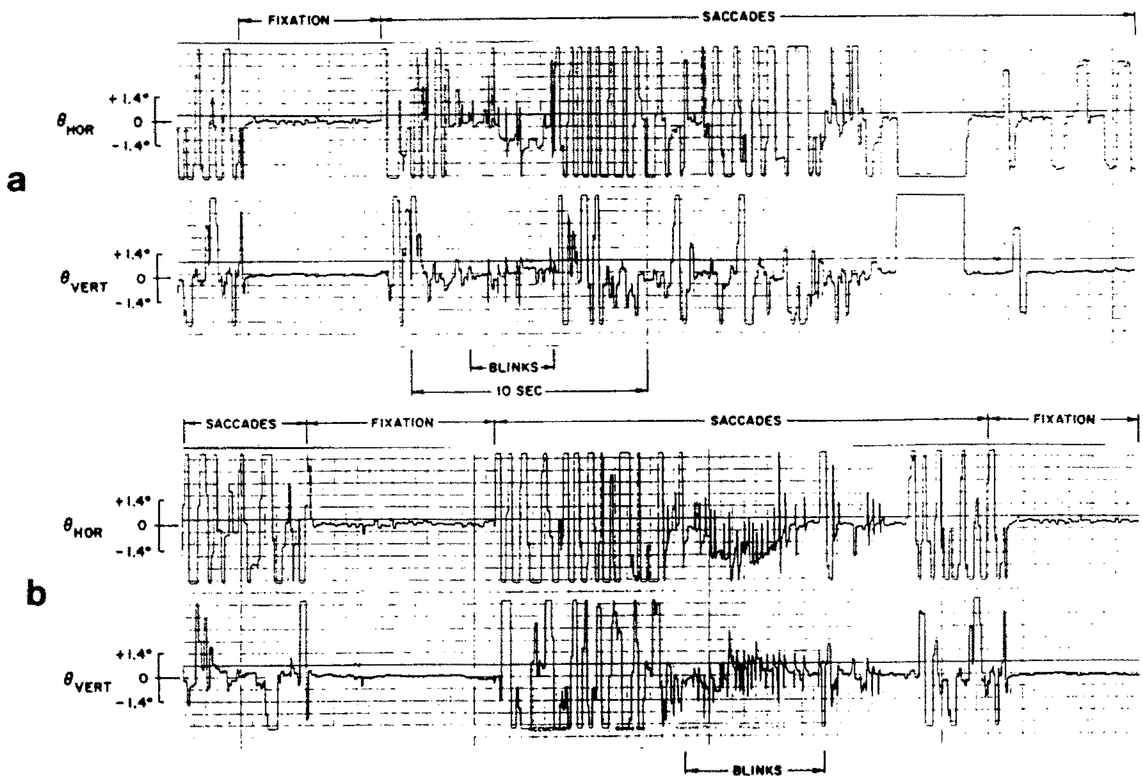

Fig. 1. (a) Horizontal (bottom) and vertical (top) eye movement recordings using the soft search coil sensor during fixation and saccades to points on the calibration matrix at the start of the experiment. (b) Eye movements after 15 min of saccadic eye movements and blinks.

Visual acuity readings as well as retinoscopic and keratometer examinations were made while the lens was adhered to the eye. Visual acuity, measured using a Snellen Chart, dropped from 20/20 to 20/100. Keratometry examination of the surface of the soft search coil lens while on the eye showed irregularities and distortions of the lens surface; these deformations are believed to be the result of sandwiching the coil between the lenses. Retinoscopic examination showed that there was no substantial change in refractive power of the eye; this was confirmed by a clinical refraction examination. These results suggest that the loss in visual acuity was mainly due to the irregularities across the lens sandwich or the multiple refractive surfaces that result from sandwiching two lenses together.

After 35 min of adhesion the lens was removed and intraocular pressure (IOP) and visual acuity were measured in addition to slitlamp, keratometer and retinoscopic examinations. IOP (using a Godmann Tonometer) dropped from 16 mmHg prior to wearing the lens to 12 mmHg in the one subject tested. (Since

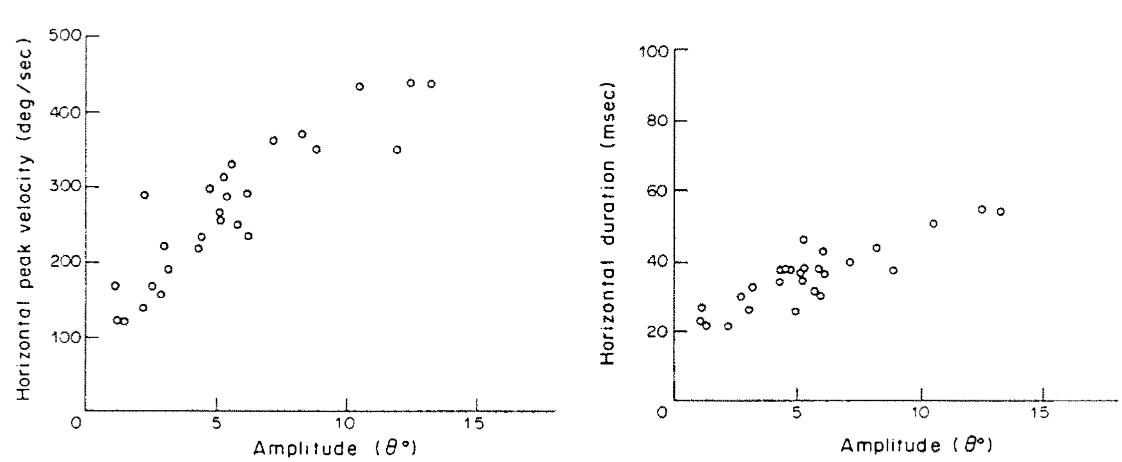

Fig. 2. Main sequence plots of horizontal saccadic eye movements recorded with sensor. Both peak velocity and duration are plotted against saccadic amplitude.

measurements were not possible while wearing the lens, IOP was measured within 1 min of removing the lens.) Visual acuity dropped from 20/20 prior to wearing the lens to 20/40; visual acuity returned to 20/20 within a 30 min period. Slitlamp examination of the corneal surface showed no surface damage or clouding of the cornea. Examination with a Keratometer showed small but noticeable irregularities in the corneal curvature. Retinoscopic examination of the eye showed no change in refractive power of the eye.

DISCUSSION

The soft search coil lens is simple to construct and comfortable for any potential subject to wear due to the low level of discomfort and lack of deleterious effects on the eye. This sensor eliminates the problem of increased intraocular pressure and the need to anesthetize the eye that are found in other sensors. Furthermore, the stability of the eye movement recordings using this search coil lens is at or below the noise level of our system (6 min arc). Periodic irrigation with distilled water using a mist sprayer is sufficient for the lens to remain firmly attached to the eye for extended periods of time. In the present experiments, the lens provided stable, reliable recordings for 35 min; longer adhesion times are possible by merely continuing the irrigation of the eye using the atomizer. Long term adhesion of the sensor was examined in one subject where the mist spraying method was used to adhere the lens to the eye for as long as 90 min.

The soft search coil lens sensor has been used in this laboratory for the last 12 months on three subjects, none of whom are contact lens wearers. Over this period of time, a single pair of soft contact lenses has been used to construct about 10 soft contact lens search coil sensors. Since the leads of search coil sensors are delicate and subject to breakage, the ability to merely replace the wire coil and reuse the soft contact lenses is an advantage.

The soft lens search coil does have some drawbacks. The most important of these is the reduction in visual acuity. While being worn, there are at least two possible sources for this reduction: distortions in the lens' front surface and multiple refracting surfaces caused by sandwiching two lenses together. This reduction in visual acuity will no doubt limit the range of experiments for which this inexpensive and simple-to-construct sensor can be used. However, there are many situations where such a sensor could be employed such as measuring eye movements in the dark, e.g. testing basic vestibular function. Other instances where the limited visual acuity associated with wearing the lens would not limit the utility of this system would be where reduced vision in one eye does not materially affect the experimental result such as recording responses to large visual field motion (optokinetic nystagmus) and where movement of both eyes are identical, i.e. during some experiments on saccades and smooth movements.

The reduction in visual acuity after removal of the lens lasts for less than 30 min and does not appear at all with shorter (less than 15 min of irrigation) experiment durations. Results from keratometry, slitlamp and retinoscopic examination of the eye suggests that irregularities in the corneal curvature are one source of the change in visual acuity. The reason for the irregularities is not clear. Possibly the tightening of the lens on the eye or the nonuniform absorption of distilled water by the cornea are responsible. Smelser (1952) showed that exposing the cornea to hypotonic solutions lead to a clouding of vision (Sattler's veil). Wilson and Stevenson (1981) found that the effects of irrigating the eye with hypotonic solution exponentially decayed over a 20 min period following last exposure to the solution, about the same as in these subjects. This slight and temporary reduction in visual acuity found after removal of the lens might be averted if the lens was adhered to the eye only during those intervals when eye movements were to be recorded (assuming the exposure time was short). Such a procedure is feasible since it takes only about 1–3 min for a loose lens to become stuck to the eye after irrigating with distilled water.

Unlike other systems where the IOP increased after wearing the search coil sensors, this system showed a reduction in IOP. The exact reason for this occurrence is not clear. However, one might postulate that the tightening of the lens on the eye gently massages the eye causing the intraocular fluid to leave the eye faster than normal. It is common practice for surgeons to massage an eye prior to surgery to reduce IOP. Tightening of the lens on the eye may act in the same manner as the surgeon's gentle massage.

Certainly improvements in the soft lens search coil sensor are possible and advantageous. Embedding the coils in a single lens would be a great improvement, however, there are many technical problems and such lenses may be very expensive due to the special care needed during manufacture to prevent damage to the coil inside the lens. Another improvement would be to create a silicone rubber contact lens that will adhere to the eye without irrigating with distilled water (Fatt, 1979; Refojo and Leong, 1981). A further improvement of the soft lens sensor would be to eliminate the lead wires from the lens by using the double induction system (Reulen and Bakker, 1982; Bour *et al.*, 1984). Such a double induction system was unavailable to test a leadless sensor. However, the double induction system and the soft lens sensor should allow measurement of precise eye movements is almost any individual who can wear a soft contact lens.

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