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RESEARCH ARTICLE

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Maintained ocular torsion produced by bilateral and unilateral galvanic (DC) vestibular stimulation in humans

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Abstract This study was designed to measure ocular movements evoked by galvanic (DC) stimulation using computerised video-oculography. Long duration (>30 s) galvanic vestibular stimulation at currents of up to 5 mA through large-area surface electrodes over the mastoid processes causes maintained changes in the ocular torsional position of both eyes in healthy human subjects. With the subject seated and the head held firmly, torsion was measured by a computer-based image-processing system (VTM). Torsion was recorded in darkness, with or without a single fixation point. With bilateral stimulation, the upper poles of both eyes always torted away from the side of cathode placement and toward the anode. For unilateral stimulation, torsion was directed away from the cathode or toward the anode. The magnitude of ocular torsion was dependent on current strength: with bilateral stimulation the peak torsion was on average 2.88° for 5-mA current intensity compared with 1.58° for 3 mA. A smaller amplitude of torsion was obtained for unilateral stimulation. The average peak torsion was the same for both eyes for all forms of stimulation. Our findings indicate that low-intensity galvanic stimulation evokes ocular torsion in normal subjects, an effect which is consistent with an action on otolith afferents.

Key words Galvanic stimulation · Vestibular nerve · Ocular torsion · Binocular · Labyrinth · Eye movement

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Introduction

Since Volta reported dizziness when he applied current across his head in the late eighteenth century (Sekitani and Tanaka 1975), galvanic stimulation has been extensively used to investigate the vestibular system. Most studies have used what we term bilateral galvanic (direct current – DC) stimulation: applying current with a positive charge (anode) through an electrode over one mastoid process and current with negative charge (cathode) through an electrode over the other. A few studies have used unilateral stimulation, where the active electrode is over one mastoid and the other electrode is at some distant location (e.g. Coats and Stoltz 1969).

The postural effects of galvanic vestibular stimulation, measured as either body motion (Coats and Stoltz 1969; Day et al. 1997), or as EMG responses in standing subjects (Nashner and Wolfson 1974; Britton et al. 1993; Fitzpatrick et al. 1994), have been explored in considerable detail. However, the oculomotor effects of galvanic stimulation have been less well documented. Horizontal nystagmus has been reported with the slow phase away and the quick phase toward the side of the cathode (Pfaltz 1970).

The present study addressed the question of whether galvanic stimulation produced other components of eye movements, specifically torsion. We used a video system (Video Torsion Measurement: VTM) with an accuracy of 0.1° (Moore et al. 1991, 1996) to record binocular torsional eye movements simultaneously during long-duration (>30 s) galvanic stimulation. We specifically sought a painless system of galvanic stimulation suitable for clinical applications. In a recent study, Zink et al. (1997) reported that bilateral transmastoid galvanic stimulation produced torsion in one eye with the upper pole of the eye torting away from the side of the cathode. They used 5 s duration square-wave current pulses with a maximum intensity of 3 mA. If current strength is increased slowly (over 30–60 s), comfortable stimulation is possible to an intensity of at least 5 mA.

This study was designed with the objective of, first, accurately recording the binocular movements produced by long-duration galvanic stimulation with ramp onset; second, examining the relationship between the torsion response and current strength, and third, comparing the binocular eye-movement responses with bilateral and unilateral stimulation. Studies of unilateral galvanic vestibular stimulation have shown that the cathode and the anode produce responses of opposite type, whether measuring body sway (Coats and Stoltz 1969) or lower-limb EMG responses (Watson and Colebatch 1997). The ability to stimulate each vestibular apparatus separately is critical to any potential clinical application.

Materials and methods

Subjects

Eight healthy subjects aged between 25 and 55 were tested. All procedures were approved by the appropriate institutional Ethics Committees and all subjects gave informed consent.

Galvanic stimulation

Surface electrodes of 600–900 mm^2 were individually cut from electrosurgical plating (3M) and placed over each mastoid process using a generous coating of electrode paste (Redux Creme, Hewlett Packard). A custom-designed, isolated current stimulator was used to deliver the desired current from a battery source over a prolonged period. For safety and comfort reasons, the current level was adjusted manually using a potentiometer and monitored continuously using a digital multimeter. Each change in current level was gradually made over 30–60 s. Current levels were read aloud from the multimeter and recorded onto the audio channel of the video tape. We used either a bilateral stimulation electrode placement (cathode applied over one mastoid and anode over the other) or unilateral stimulation electrode placement (either cathode or anode over one mastoid and the other electrode at an indifferent site). The vertebra prominens (C7) was used as the site for the indifferent electrode, as it was well away from both stimulating electrodes and the recording apparatus and was well tolerated.

Procedure

Subjects were seated with their head held so that Reid's line (the line joining the inferior margin of the orbit and the upper margin of the external auditory meatus) was held about 7° nose up relative to earth horizontal. This is a standard position, which is both comfortable and allows for comparable positioning of the otoliths across subjects. Head and shoulders were held firmly by padded supports. Binocular horizontal, vertical and torsional eye positions were recorded continuously using video techniques (see below). Two series of experiments were performed:

1. We measured torsion in five normal subjects in response to bilateral galvanic stimulation, and measured the relationship between current intensity and magnitude of oculomotor response. Perceptual tests were also performed during these experiments (to be reported separately). Initial cathode placement was to the left in three subjects and to the right in two subjects. Following baseline measurements, the initial perceptual tests, lasting approximately 1 min, were performed, and then the current was applied (onset at 0.6 mA) and increased gradually to 5 mA. The subject fixated on a target (see below) during the increase in current and for the first 30 s at 5 mA. The perceptual tests were then repeated followed by 30 s of recording in complete darkness in order to detect any nystagmus potentially suppressed by visual fixation. The subject fixated on the target for a further period of at least 10 s before the current was gradually returned to 0 mA. At 0 mA, the same sequence was followed, except that recording in complete darkness was not performed because no nystagmus was to be expected under these conditions. The electrode polarity was then reversed and the entire sequence was repeated (see Fig. 1). The electrode polarity was then returned to the original, and the current was gradually increased to 3 mA, where the subject fixated on the target for 2 min before the current was gradually reduced to 0 mA. After 30 s, the same sequence was followed with the electrode polarities reversed.

2. The second series of experiments was also performed on five normal subjects, including two subjects studied in the earlier experiments, to compare the effects of bilateral stimulation with those of unilateral cathodal and anodal stimulation. Bilateral stimulation was performed first, cathode left/anode right followed by cathode right/anode left. Unilateral cathodal stimulation was then performed, cathode left followed by cathode right (in both cases, the reference electrode was on C7). Finally, unilateral anodal stimulation was performed, anode left followed by anode right. In all cases, the current was applied at 0.6 mA and gradually increased manually to 5 mA. During delivery of 5 mA current, the subject fixated on the target for 60 s, then gazed at the point where it had been (in complete darkness) for 30 s, and finally fixated on the target for a further 10 s. The current was then gradually returned to 0 mA, where it remained for at least 60 s before electrode polarity was reversed. The subject fixated on the target during periods of changing current intensity and periods without stimulation.

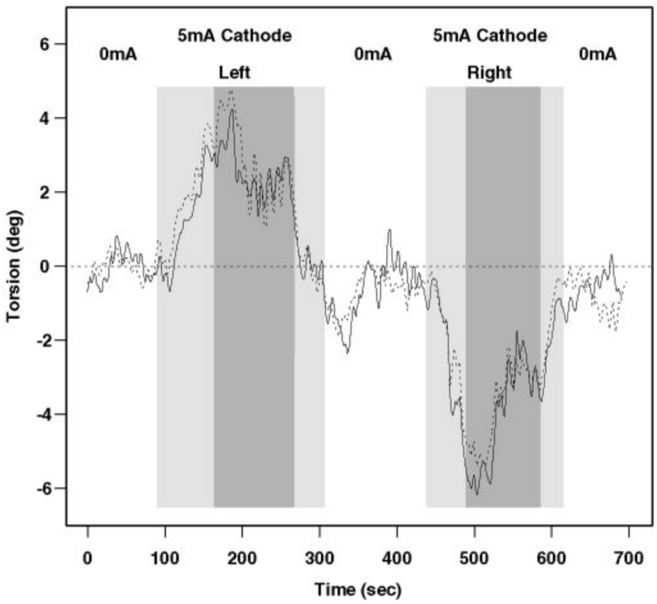

Fig. 1 Torsion during bilateral galvanic stimulation. Time series of ocular-torsional position of the left eye (*solid line*) and right eye (*dashed line*) of a typical subject during bilateral galvanic stimulation whilst fixating a small, dim visual target in an otherwise darkened room. The *light and dark grey regions* indicate periods of changing and maintained stimulation, respectively. *Unshaded regions* indicate an absence of galvanic stimulation. The value of maintained current is 5 mA for both polarities of bilateral stimulation. Current was designated to be negative when the polarity was cathode right / anode left and positive when the polarity was cathode left / anode right

Ocular-torsion measurement and analysis

A full description of the procedure and calibration of the method for the measurement of ocular-torsion position (OTP) has been published previously (VTM: Moore et al. 1991, 1996). The resolution of this method is 0.1° of ocular torsion, and a low sampling rate of 2 Hz was used for maximum sensitivity. The OTP of all subjects was measured binocularly using half-silvered ("hot") mirrors (Coolbeam, OCLI, Santa Rosa), which allowed measurement during unobstructed vision. The pupils of both eyes were constricted by 2% Pilocarpine; the eyes were illuminated with infrared light sources; for each eye, a close-up image of the iral pattern was reflected by a hot mirror onto a lipstick-sized (approximately 6-cm length ×1.5 cm diameter) CCD camera (Panasonic WV-CD1E). The cameras, mirrors and infrared iral illumination systems were mounted on a thermoplastic mask (SanSplint, Smith and Nephew), which was individually moulded to the subject's face and held in place by Velcro straps. This tight-fitting, but comfortable "wrap-around" mask minimised camera slippage relative to the eye, and our measures of eye position at the start and end of the test showed that there was no detectable camera slippage.

Visual targets

A cardboard sheet with a circular aperture 8 cm in diameter was placed in front of the active LCD screen of a laptop computer (Contura 420CX, Compaq Computers) placed at eye height, 60 cm from the subject, in the otherwise darkened room. The laptop screen was run at very low luminance and a sheet of neutral-density gelatin film (Lee Neutral Density Gel 200) was placed over the screen in order to prevent subjects seeing the edges of the individual pixels. Black velvet covered the cardboard and was draped across the laptop's keyboard and its mounting. In this way, the only visual stimulus during testing was a circular patch of very dim grey-blue light from the LCD screen of the laptop with a visual angle of 7.6° and a luminance of 0.2 candelas/m^2, in the centre of which was the fixation target, a small spot or circle of white light, subtending 1.5° of visual angle. This laptop computer was also used for carrying out visual perceptual tasks. To allow testing in complete darkness, the laptop screen visible through the aperture was covered by black velvet so that no visual stimuli at all were visible to the subject.

All data were recorded onto SVHS videotape using two SVHS tape recorders and analysed after the test session. The right hand rule was used, so that clockwise ocular torsion (where the upper pole of the eye rotated toward the subject's right shoulder) is positive and counter-clockwise ocular torsion is negative. At the start of each experiment, reference images of both eyes were recorded for 2 min while the subject gazed at the fixation point. The average value of the OTP measured during this period was taken as the baseline measure for that subject and arbitrarily given the value of 0° torsion. Prior to the initial current being applied for each subsequent condition of the experiment, the reference or resting torsional position was also reset to 0° torsion. Two values were used to represent the response to galvanic stimulation in each subject, for a given electrode placement and current intensity. We calculated an average of the OTP for the 5 s either side of the initial peak torsion value ("peak") and an average of 10 s of maintained OTP ("tonic"), immediately prior to stimulus reduction.

Results

All subjects tolerated the current stimuli well and reported minimal discomfort.

Bilateral stimulation

Galvanic stimulation produced ocular torsion in all subjects. With bilateral stimulation the upper poles of both eyes always torted around the visual axis away from the side of the cathode and toward the side of the anode (Fig. 1). There was usually a peak of ocular torsion soon after reaching maximum current intensity, followed by a reduction to a lower amplitude during maintained current (Fig. 1). Both eyes showed similar torsion magnitudes and direction. During and after current-intensity reduction, the direction of ocular torsion reversed. A few beats of horizontal or horizontal/torsional nystagmus were observed in most subjects during the change in galvanic stimulation, even with the fixation target present.

The individual and group mean values obtained are shown in Fig. 2. Ocular torsion was of significantly greater amplitude for 5 mA than for 3 mA current intensity, both in terms of the "peak" (t_8=3.97, P=0.004) and the "tonic" (t_8=3.62, P=0.007) ocular-torsion measures (see Table 1).

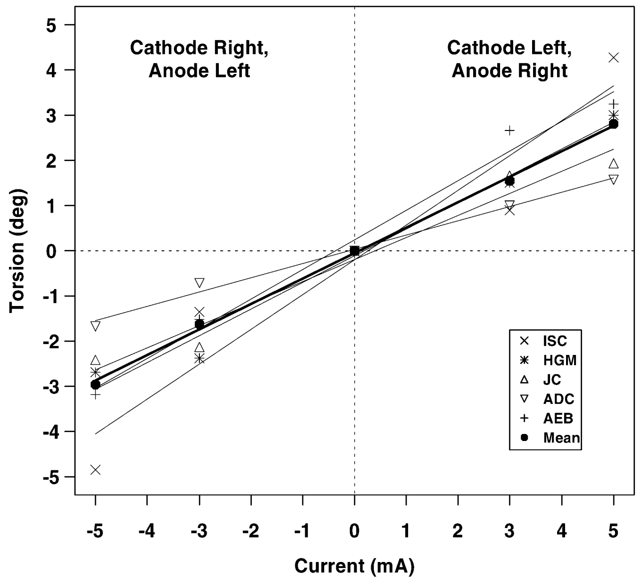

Fig. 2 The mean peak torsion (averaged over both eyes for 5 s either side of the initial peak value reached) for each subject as a function of current strength during bilateral galvanic stimulation. The mean peak torsion for the group is shown by the *solid circles*. The *thin lines* indicate the best-fitting straight lines for each subject; the *heavy line* indicates the group mean

Table 1 Peak and tonic ocular torsional position (in deg) at four polarities / levels of bilateral galvanic stimulation (-5, -3, 3 and 5 mA) and baseline (0 mA) for five subjects

Current (mA)	OTP: Peak (mean ± s. e.)	OTP: Tonic (mean ± s. e.)
–5	–2.96 ± 0.53	–1.59 ± 0.30
–3	–1.62 ± 0.29	–0.96 ± 0.13
0	0.00 ± 0.00	0.00 ± 0.00
3	1.54 ± 0.32	0.77 ± 0.22
5	2.80 ± 0.48	1.64 ± 0.22

Unilateral stimulation

With unilateral stimulation, the eyes always torted away from the side of the cathode or toward the side of the an-

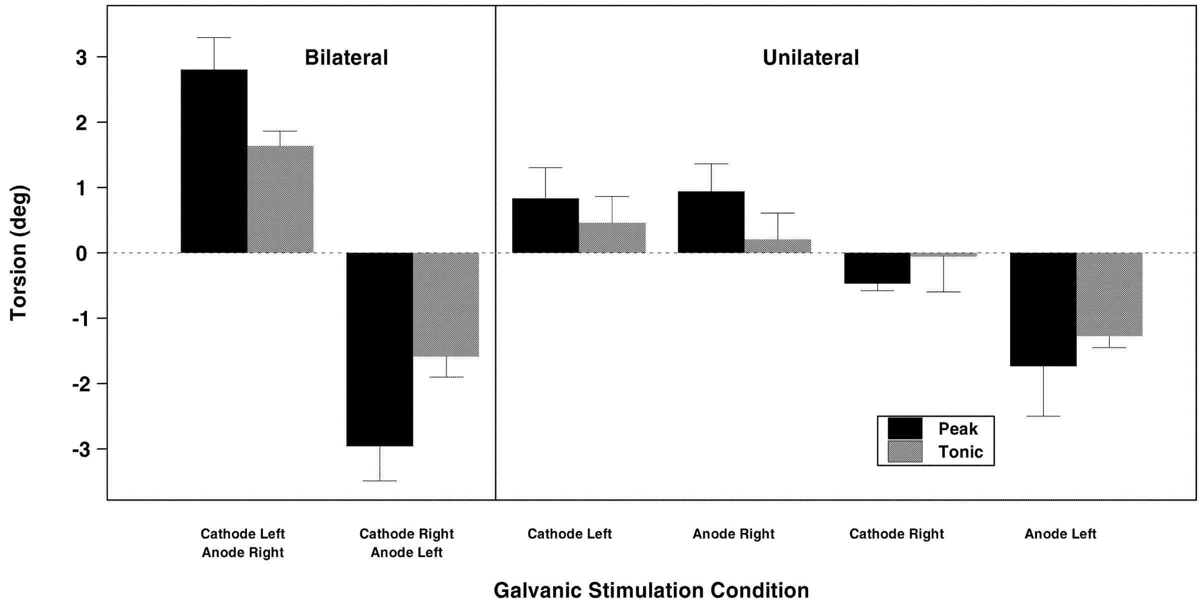

Fig. 3 Mean peak and tonic torsion (±1 s.e.) as a function of galvanic-stimulation condition

ode, depending on which electrode was applied over the mastoid process; Fig. 3. Thus, the ocular torsion produced by unilateral cathodal and unilateral anodal stimulation to the same side were of opposite direction. Although unilateral cathodal and unilateral anodal stimulation produced ocular torsion of opposite direction, there was no significant difference between the two in terms of amplitude of either "peak" (t_6=1.55, P=0.17) or "tonic" (t_6=0.71, P=0.50) ocular torsion (Fig. 3). The sum of the torsion induced by unilateral cathodal and unilateral anodal stimulation was smaller than that to transmastoid stimulation, but these differences were not statistically significant, neither in terms of the "peak" (t_7=1.73, P=0.13) nor the "tonic" (t_7=0.89, P=0.40) measures (Fig. 3).

For both bilateral and unilateral stimulation, the ocular torsion obtained during stimulation was similar for each eye, although a large degree of disconjugate drift was observed for two of the eight subjects. However, even in these subjects, the magnitude of the response to the galvanic stimulus, with respect to their drifting baseline value, was similar for both eyes. Both of these subjects had corrected vision and had removed their corrections for testing, so we attribute the torsional drift to inadequate binocular oculomotor coordination due to their poor visual acuity.

Given the experimental design, in particular the limitations regarding precise timing of current onset, it was not possible to determine response latencies. However, in all subjects, the peaks in OTP values occurred several seconds after the maximum current level was reached (e.g. Fig. 1).

In no subject was there a sustained illusion of head or body tilt, or other motion, with the maintained galvanic stimulation. However, most subjects reported an illusion of self motion at current onset or during changing current intensity. With bilateral stimulation, seven of eight subjects reported sensations of roll-tilt toward the cathode during the increase in current and away from the cathode during current decrease. Two of the subjects who perceived roll-tilt also reported sensations of brief yaw rotation. These sensations diminished during constant current stimulation. Similar, but milder sensations were reported during unilateral stimulation.

Discussion

We have shown that galvanic stimulation of up to 5 mA delivered through electrodes on the mastoid processes produces ocular torsion without prominent nystagmus. This confirms and extends a recent result by Zink et al. (1997). In particular, we have shown that the torsion occurs during maintained galvanic current, that its magnitude depends on current strength, that it is similar in both eyes and that it occurs in response to unilateral stimulation. This is the first time that unilateral galvanic stimulation has been shown to produce torsion.

Most previous studies of the effects of galvanic stimulation on oculomotor responses (e.g. Pfaltz 1970) have, unlike us, found nystagmus, possibly because rapid current-intensity change is more likely to produce nystagmus than the slow change we used. Although the fixation point would act to suppress nystagmus, even in complete darkness we found very little nystagmus.

In response to the 5 mA bilateral stimulus, there were large individual differences between subjects, but in all subjects the direction of the torsion induced by a given stimulus polarity was identical: the upper poles of both eyes torted away from the side of the cathode and / or toward the side of the anode. The average magnitude of the peak torsion was 2.88°, which is comparable to the torsion produced by about 30° of roll-tilt around a nasooccipital (X) axis (Diamond et al. 1979). Even in the subject with the smallest torsion, the magnitude of the peak galvanic-induced torsion (1.6° at 5 mA) was larger than the spontaneously occurring, slow torsional eye movements (around 1° peak to peak) that are always present, even during fixation (Collewijn et al. 1985). Clear peaks of torsion were often observed following changes in stimulating current intensity, and changes in current were more often associated with illusions of subjective motion. Zink et al. (1997) used a square-wave galvanic stimulus of lower intensity, and this may explain why the amplitude of ocular torsion reported by them is similar to that described here.

The maintained torsion occurred in the absence of a maintained illusion of roll-tilt, i.e. the eyes remained torted, but roll-tilt of the body was only transiently perceived. This is in accord with recent evidence of a dissociation between OTP and perceived roll-tilt (Curthoys and Betts 1997; Wade and Curthoys 1997). In the present study, large areas of the body were in contact with the chair and supports during the galvanic vestibular stimulation, and we presume that this somatosensory stimulation influenced the perception of the body's position in space, but had minimal effect upon ocular torsion.

We have shown, using unilateral galvanic stimulation, that both cathodal and anodal stimulation cause conjugate ocular torsion, the direction of which is dependent on mastoid electrode polarity. The response to bilateral labyrinth galvanic stimulation is thus contributed to by both the cathode and the anode. Studies in animals have demonstrated that cathodal galvanic stimulation results in activation of vestibular afferents, and anodal stimulation results in their inhibition, through an action at the spike trigger zone of primary afferents (Goldberg et al. 1984). Cathodal and anodal galvanic stimulation produce opposite types of postural (Coats and Stoltz 1969) and lower-limb EMG (Watson and Colebatch 1997) responses in humans. The small size of the responses to unilateral stimulation may, however, limit their value as a clinical test.

The population of vestibular afferents activated by galvanic stimulation in human subjects is unknown. In animal studies, irregularly firing afferents show higher sensitivity to galvanic stimulation than regularly firing afferents (Goldberg et al. 1984), but there is no differential sensitivity between the afferents innervating different vestibular endorgans (Goldberg et al. 1984; Kleine and Grüsser 1995). Both galvanic stimulation and high-intensity clicks produce EMG responses in soleus (Watson and Colebatch 1998) and sternocleidomastoid (Watson et al. 1998), which have similar latencies and waveforms. Given the strong evidence from animal studies that high-intensity clicks specifically activate the saccule (Murofushi and Curthoys 1997; Didier and Cazals 1989; McCue and Guinan 1994), the present results raise the possibility that galvanic stimulation may be particularly effective for saccular afferent fibres. Baloh et al. (1992) reported two patients with profound abnormalities of lateral semicircular-canal function, who had preserved galvanic-evoked oculomotor responses in combination with normal otolith-ocular responses, suggesting a predominant action of galvanic stimulation on otolith pathways. Recent reports (Inglis et al. 1995; Day et al. 1997) have emphasised the maintained body tilt that occurs with prolonged galvanic stimulation, which is also consistent with an action on otolith rather than canal afferents. Finally, the predominant ocular torsion in the absence of any nystagmus favours a selective action of galvanic stimulation on otolith afferent fibres in humans.

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