Comparison of Human Ocular Torsion Patterns During Natural and Galvanic Vestibular Stimulation

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Schneider, Erich, Stefan Glasauer, and Marianne Dieterich. Comparison of human ocular torsion patterns during natural and galvanic vestibular stimulation. J Neurophysiol 87: 2064–2073, 2002; 10.1152/jn.00558.2001. Galvanic vestibular stimulation (GVS) is reported to induce interindividually variable tonic ocular torsion (OT) and superimposed torsional nystagmus. It has been proposed that the tonic component results from the activation of otolith afferents. We tested our hypothesis that both the tonic and the phasic OT are mainly due to semicircular canal (SCC) stimulation by examining whether the OT patterns elicited by GVS can be reproduced by pure SCC stimulations. Using videoculography we measured the OT of six healthy subjects while two different stimuli with a duration of 20 s were applied: 1) transmastoidal GVS steps of 2 mA with the head in a pitched nose-down position and 2) angular head rotations around a combined roll-yaw axis parallel to the gravity vector with the head in the same position. The stimulation profile was individually scaled to match the nystagmus properties from GVS and consisted of a sustained velocity step of 4–12°/s on which a velocity ramp of 0.67–2°/s² was superimposed. Since blinks were reported to induce transient torsional eye movements, the subjects were also asked to blink once 10 s after stimulus onset. Analysis of torsional eye movements under both conditions revealed no significant differences. Thus we conclude that both the tonic and the phasic OT responses to GVS can be reproduced by pure rotational stimulations and that the OT-related effects of GVS on SCC afferents are similar to natural stimulations at small amplitudes.

INTRODUCTION

Transmastoidal galvanic vestibular stimulation (GVS) induces eye movements with horizontal (Buys 1909) and torsional (Hitzig 1898) components by activating the vestibulococular reflex (VOR). On the side of the cathode, the applied current is believed to depolarize the vestibulocellular afferent’s spike trigger site, which extends 10–50 µm from the synapse to the first level of myelination (Goldberg et al. 1984). The thus depolarized afferent membrane leads to an increase in the firing rate. On the anodal side, this process is reversed. The galvanic activations are similar for the afferents of every vestibular end organ (Goldberg et al. 1984; Kleine and Grüsser 1996). Unilateral excitation of either utricular or semicircular canal (SCC) nerve branches induces compensatory eye movements with a predominantly torsional component, with the upper side of the bulbus rotating away from the stimulated side (Suzuki et al. 1969). Transmastoidal galvanic stimulation thus mimics a head movement toward the side of the cathode, with utricular fibers signaling a tilt and SCC fibers signaling a rotation of the head. Since irregular afferents have a smaller postspike recovery time constant, their galvanic sensitivity is sixfold greater than that of regular afferents (Goldberg et al. 1984). The contribution of irregular fibers to the horizontal VOR is significant if the head is rotated with velocity steps (Angelaki and Perachio 1993) but diminishes if the stimulus is sinusoidally modulated (Angelaki and Perachio 1993; Minor and Goldberg 1991). Sustained current steps induce two distinct types of torsional eye movements: first, a tonic ocular torsion (OT) of both eyes, and second, superimposed torsional nystagmus. The tonic OT has been attributed to the activation of otolith afferents (Watson et al. 1998; Zink et al. 1997, 1998). In some individuals, GVS can evoke more tonic OT than nystagmic eye movements, whereas in others a considerable nystagmus response can be observed. Two explanations are discussed in the literature for this interindividual variability of OT patterns. One proposed explanation is that the threshold for the activation of SCC afferents varies (Zink et al. 1997, 1998). Another proposed explanation is that the contribution of the otolith afferents varies (Kleine et al. 1999). We recently proposed a third possibility, namely that interindividually variable nystagmus frequencies and amplitudes could lead to the observed phenomenon. On the basis of theoretical considerations, we concluded that the effect of SCC afferents on OT prevailed over the effect of utricular pathways, although all vestibular afferents are activated equally by GVS (Schneider et al. 2000a).

The purpose of the present study was to test this hypothesis by a direct comparison of torsional eye movements elicited by GVS and by natural SCC stimulations. If all the observed OT patterns could be explained by a dominant SCC contribution during GVS, similar results should be obtained with a pure rotational stimulation of the head that mimics the afferent firing rate induced by GVS. Since blinks during GVS induce transient torsional eye movements (Schneider et al. 1999), we additionally hypothesized that blinks should have the same effect during pure SCC stimulations. The preliminary findings of this study were presented at the 26th meeting of the Society for Neuroscience (Schneider et al. 2000b).

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METHODS

Six healthy subjects (1 female, 5 males; 32 ± 2.5 yr of age, mean ± SD) participated in the experiments. The subjects gave their informed consent after being briefed about the examination. The experiments were approved by the local ethics committee (approval numbers 87/96 and 212/96).

The subjects kneeled on a rotating chair (Toennies turntable) with their heads restrained in a pitched nose-down position by a forehead and a chin rest (schematic drawings of heads at top of Figs. 1 and 4). The distance between the chin rest and the center of rotation was 0.5 m. We determined the orientation of the Reid plane (Blanks et al. 1975) by applying one black skin marker to the inferior margin of the left orbit and another one to the left tragus at the level of the auditory canal center. After each experiment we recorded the subject’s head with a video camera. From these images we calculated the angle between a vertical line in the background and a line connecting the two markers. The thus calculated mean deviation of the Reid plane between a vertical line in the background and a line connecting the canal center. After each experiment we recorded the subject’s head with a video camera. From these images we calculated the angle between a vertical line in the background and a line connecting the two markers. The thus calculated mean deviation of the Reid plane from the earth horizontal was 58 ± 6°. With the angle of 25 ± 6° between the lateral SCC planes and the Reid stereotoxic planes obtained from 10 human skulls (Blanks et al. 1975), the deviation for the lateral SCC planes of the participants in our experiment from the earth horizontal was roughly estimated to be 33 ± 8°. In RESULTS we simplified the estimation of afferent GVS sensitivities by approximating these anatomical data with the mathematically more convenient alignment of SCC planes outlined in Fig. 1.

Two stimulation paradigms were used to induce torsional eye movements. In the first paradigm current steps of 2 mA were applied by means of two electrodes placed binaurally over both mastoids. The electrodes had a surface of 15–20 mm² and were made of rubber foam permeated with a NaCl-based electrode gel.

The second paradigm consisted of angular head rotations (aVOR) around a combined roll-yaw axis parallel to the gravity vector with the subject’s head in the same position as during GVS. This head position was chosen to allow a roughly unimodal stimulation of the canals on one side, i.e., an activation (deactivation) of the right canals and a deactivation (activation) of the left canals during a (counter-) clockwise rotation around the earth-vertical axis. The stimulation profile consisted of a sustained velocity step on which a velocity ramp was superimposed. The slope of the ramp was calculated from the inverse torsion pendulum model of the cupular dynamics with a dominant time constant of τ = 6 s (Dai et al. 1999; Fernández and Goldberg 1971). This model-based approach was assumed to keep the afferent activation constant at the level induced by the initial velocity step (Fig. 4, bottom row). Initially, velocity steps of ν = 5°/s were used. The corresponding ramp acceleration was calculated with a = ω² = 5°/s². For the torsional eye movements obtained from aVOR and GVS, we determined means across time for both quick phase amplitudes e and slow phase velocities p. For each subject a scaling factor k = (e_aVOR/ν_aVOR + p_aVOR/p_aVOR)² was calculated, then multiplied by ν to obtain the step amplitude of a second aVOR stimulation. With the thus adjusted second aVOR step velocities of 4–12°/s and ramp accelerations of 0.66–2°/s², we hypothesized that torsional eye movements would be obtained with similar properties to those observed during GVS. The maximal utricular shear forces expected from the off-axis head rotation were on the order of 0.003 g and were thus negligible. Only the effects of the second aVOR stimulation are reported in RESULTS.

GVS and aVOR stimulations lasted 20 s and were repeated four times with alternating polarity or direction. In addition, the subjects were asked to intentionally blink as soon as they heard an acoustic signal, which was triggered 10 s after each stimulation onset under both conditions.

Experimental equipment

An off-the-shelf digital video camcorder (Sony DCR-7000E PAL) was used to monocularly measure movements of the left eye. The camera was attached to a rotating chair and was adjusted so that the subjects were able to look directly into the camera optics. The so-called “NightShot” functionality of the camera provided the means for recording the eyes in total darkness with an infrared illumination. A fluorescent fixation point in a straight ahead position was used to ensure pure cyclo-rotations of the eye while horizontal and vertical eye movements were suppressed. The OT was calculated from a pair of markers applied to the sclera (Fig. 2) (Clarke et al. 1999). The markers consisted of an infrared absorbing cosmetic pigment (Chiron Vision, Berlin, Germany). They were applied to the sclera by means of a sterile surgical pen. Prior to the application the pen was permeated with a solution prepared from a small amount of pigment and a drop of water. The images were recorded on tape with a sampling rate of 50 Hz (25 Hz interfaced) and were later analyzed by a custom-made image processing software package (APPENDIX and Fig. 2).

Both the current source for the GVS and the servo-driver for the rotating chair were controlled by a computer with an accuracy of 12
both experiments blinks triggered quick phases with amplitudes larger than the quick phase amplitudes of normal nystagmus. In the subsequent paragraphs we quantitatively compare the OT parameters from GVS and aVOR, which are summarized in Table 1.

**Nystagmus analysis**

We compared the nystagmus intensity, the SPV, the slope of the SPV, the corrected OT, the beating field of the original OT, and the time constant of the neural integrator dynamics for GVS and aVOR. There was no significant difference at a 5% level of confidence between the two paradigms for any of the given variables. The beating field, however, was greater during GVS than during aVOR, and the difference almost reached significance level \[ F(1, 5) = 6.32, P = 0.054 \].

Although the nystagmus parameters differed from subject to subject, the correlation between GVS and aVOR was significant. To calculate the correlation coefficient for, e.g., the nystagmus intensity, we correlated the values for GVS with the values for aVOR from the column denoted with “Int” in Table 1. For nystagmus intensity, the correlation coefficient was 0.93 \((P < 0.01)\) and for SPV 0.97 \((P < 0.005)\). The correlation coefficient for the SPV slope was 0.88 \((P < 0.05)\). The beating field of the original OT and the corrected OT correlated with 0.86 \((P < 0.05)\) and 0.93 \((P < 0.01)\), respectively. These findings imply an intrasubjective similarity between the OT patterns elicited by GVS and by aVOR (Fig. 4). The addition of artificial inverse nystagmus to the original OT recordings eliminated the influence of nystagmus beats. There was a significant correlation across time of 0.92 \((P < 0.001)\) between the corrected OT and the theoretical response to a step input expected from the torsional neural integrator. This leaky neural integrator is known to have a time constant of around 2 s (Seidman et al. 1994). These findings are illustrated by the dashed and dash-dotted plots of Fig. 4.

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**RESULTS**

Figures 3 and 4 clearly show that appropriately adjusted rotational stimuli were able to induce OT patterns that resembled those induced by GVS steps. During both stimulations, an interindividually variable amount of phasic OT, i.e., nystagmus, was observed, which was superimposed on a tonic OT. In both experiments blinks triggered quick phases with amplitudes larger than the quick phase amplitudes of normal nystagmus. In the subsequent paragraphs we quantitatively compare the OT parameters from GVS and aVOR, which are summarized in Table 1.

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Blink analysis

Eye movements following blinks consistently showed the same pattern as nystagmus: they consisted of a quick phase toward the resting position of the eye followed by a slow phase with an exponential trajectory in the opposite direction. This pattern can be observed in both the GVS and the aVOR paradigms. The compensatory algorithm worked equally well for both nystagmus and blink-related eye movements (Fig. 2, bottom row). Thus the dynamics of torsional eye movements following a blink are similar to the dynamics of torsional nystagmus. The mean SPV following a blink (3.41 ± 2.48°/s) was significantly higher \( F(1,11) = 25.99, P < 0.0003 \) than the mean nystagmus SPV (0.95 ± 0.58°/s). Similarly, the average torsional quick phase amplitudes induced by blinks (1.99 ± 1.15°) were significantly larger \( F(1,11) = 76.70, P < 0.0001 \) than the amplitudes of torsional nystagmus beats (0.33 ± 0.21°). The blink-induced quick phase amplitudes were not significantly different between the two paradigms \( F(1,5) = 5.53, P > 0.05 \).

It is worth mentioning that even small blinks, which did not occlude the pupil, were observed to trigger quick phases (Fig. 2, right column).
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For both stimulation conditions, the response of the corrected OT to the stimulus onset consisted of an exponential trajectory that saturated with time constants in the range of 2 s. The corrected OT showed a sensitivity of 1.76 \( \pm \) 0.26/aVOR.\(^1\) The SPV sensitivity to GVS was 0.45 \( \pm \) 0.26/s/mA, and the SPV gain for aVOR was 0.22 \( \pm \) 0.11. From the two slow phase velocities \( P_{GVS} \) and \( P_{aVOR} \) the galvanically induced increase in afferent spike frequency \( f_{GVS} \) can be estimated by \( f_{GVS} = f_{aVOR} \cdot P_{GVS}/P_{aVOR} \). The naturally induced spike frequency \( f_{aVOR} \) can be estimated on the assumption that the sensitivity of canal afferents to head rotations in humans is similar to the sensitivity of SCC = 0.55 Hz/deg/s measured in monkeys (Fernández and Goldberg 1971). The initial step velocity \( v \) of the rotational stimulus thus leads to an afferent activation of \( f_{aVOR} = s_{SCC} \cdot v/\sqrt{3} \) (Table 1, last column). For simplicity, the last equation assumes the geometrical alignment of SCCs given in methods (Fig. 1). Since \( v \) in this approximated configuration acts along the vectorial sum of all activation vectors, the projection of the total activation caused by \( v \) onto a single SCC vector can be calculated with \( v/\sqrt{3} \). By inserting the equation for \( f_{aVOR} \) into the equation for \( f_{GVS} \), the mean sensitivity of the SCC afferents to transmastoidal currents was roughly estimated to be 1.00 \( \pm \) 0.46 Hz/mA if the irregular afferent fibers are not involved in these eye movement responses. Alternatively, the galvanic sensitivity can be calculated from the corrected OT, instead of the SPV, by using the same set of equations. With this procedure a value of 1.26 \( \pm \) 0.34 Hz/mA was obtained, which was not significantly different from the SPV deduced value \( [F(1,5) = 4.52, P < 0.05] \).

DISCUSSION

Relative otolith and SCC contributions

The hypothesis behind our study was that head rotations around a combined roll-yaw axis should be able to elicit torsional eye movements with properties similar to those seen during GVS. The statistical analysis of the OT recordings indeed revealed no significant differences between the two conditions. This result supports our hypothesis. It should be stressed that these head rotations, which are known to activate only canal pathways, were able to cause a prolonged tonic OT. The presence of this tonic component was the basis for the conclusion that the activation of otolith pathways must play a significant role during GVS (Watson et al. 1998; Zink et al. 1997, 1998). Similarly, posturographic studies have revealed a maintained body tilt during GVS, an observation from which the same conclusion regarding an otolith contribution was drawn (Day et al. 1997; Inglis et al. 1995). However, there is evidence even in the older literature that prolonged tilt reactions can be induced by pure rotational stimuli as well. For example, optokinetic patterns that constantly rotate around the roll axis have been shown to induce both a deviation of perceived gravity by \( \pm 40^\circ \) and a maintained postural tilt (Dichgans et al. 1972). These patterns cannot only induce offset positions of OT, as has recently been shown by Lee et al. (2000), but also torsional eye movements with similar properties as those known from GVS (Romberg and Ohm 1944). In

\(^1\) The leaky neural integrator transfer function with its time constant \( \tau \) transfers head angular velocity \( \dot{v} \) to torsional eye position (OT) by OT = \( \dot{v}/\tau \cdot (\tau \cdot s + 1) \). Solving this equation for \( g \) at \( s = 0 \) yields a static gain of \( g = \dot{v}/(\tau \cdot \dot{v}) \). Thus the corrected OT gain to aVOR stimuli is dimensionless.
addition, it has long been known that SCCs contribute to the perception of the visual vertical (Stockwell and Guedry 1970). More recent model-based studies indicate that (post-) rotational stimuli have a systematic influence on the internal estimate of the gravito-inertial force and hence on the properties of the VOR (Merfeld et al. 1999, 2001; Zupan et al. 2000). Specifically, the VOR model of Merfeld (1995) predicts a deviation of the gravity estimate in the presence of pure SCC stimulation as applied in our study. This deviation may cause a tonic OT. Thus the observation of a tonic OT does not necessarily justify the view that otolith pathways must be involved in the GVS-induced eye movements.

Pure SCC stimulations and GVS induced OT patterns with similar phasic and tonic parameters. Although these parameters vary among subjects, a statistical analysis has shown that there is no intrasubjective difference between the two paradigms. From a statistical point of view, this result may appear trivial. Since the stimulation velocity was individually adjusted to approximately obtain the same eye movements as those seen during GVS, the independent sample assumption required for a statistical test was violated for mean SPV and mean nystagmus amplitude. Not surprisingly, the differences between these parameters did not reach significance level. The surprising result of this study, however, is that it was possible to adjust the rotational stimulus by a single scaling factor so that GVS and aVOR-induced eye movements became statistically indistinguishable for all analyzed parameters. In the context of the GVS-related literature, which consistently attributed the tonic components of GVS responses to otolith activations (Day et al. 1997; Inglis et al. 1995; Kleine et al. 1999; Watson et al. 1998; Zink et al. 1997, 1998), it was surprising to measure eye movements that we were familiar with from GVS, although only canals and no otoliths were stimulated. The statistical analysis of the data obtained from aVOR stimulation with intrasubjectively adjusted amplitudes shows that with appropriately chosen angular head velocities it was possible to generate eye movements that are statistically indistinguishable from GVS-induced eye movements.

These similarities lead to the conclusion that during GVS the activation of SCC afferents alone is sufficient to induce the observed OT patterns; an otolith contribution is not necessary for either the so-called tonic OT (Watson et al. 1998; Zink et al. 1997, 1998) or the variability of tonic versus phasic OT seen among subjects (Kleine et al. 1999). However, if utricular afferents contributed to the OT during GVS, this effect should become apparent in a larger corrected OT and a higher beating field of the original OT, i.e., in a higher tonic component. This increase can be expected since a galvanic stimulation of the utricular nerve branch alone is known to induce OT in the same direction as a galvanic stimulation of the afferents originating from vertical SCCs (Suzuki et al. 1969). Since transmastoidal GVS resembles a combined utricular and SCC activation (Goldberg et al. 1984; Kleine and Grüsser 1996), the otolithic and SCC effects might be additive and thus lead to a higher OT than during a pure SCC stimulation. Consequently, we observed slightly increased values for both the beating field and the corrected OT during GVS. Similarly, the afferent galvanic sensitivity estimated from the corrected OT was increased compared with the sensitivity deduced from the SPV. The increases were on the order of 10–26%, but did not reach significance at a confidence level of 5%. This may be the amount by which otolith pathways contributed to the OT during GVS. At first glance it might appear contradictory that, on the one hand, otolith and SCC fibers are activated equally by GVS (Goldberg et al. 1984; Kleine and Grüsser 1996) but that, on the other hand, OT is dominated by SCC effects. This apparent contradiction is resolved if we take into account that the known gains and sensitivities of the utricular (Bucher et al. 1992; Clarke et al. 1999; Fernández and Goldberg 1976) and SCC (Fernández and Goldberg 1971; Seidman et al. 1994; Tweed et al. 1994b) pathways differ by a factor of more than 3 for the torsional VOR. A change of 1 Hz in the SCC fiber activities will roll the eye by an amount of 0.95°, while the same change in the activation of utricular fibers will roll the eye by an amount of only 0.27°. The observation of eye movements dominated by SCC inputs is thus compatible with the notion of equal otolith and SCC fiber activation during GVS. In an earlier study (Schneider et al. 2000a) we estimated from these theoretical considerations that the relative contribution of otolith afferents to the observable GVS-induced OT amounts to a maximum of 22% if the fibers of all vestibular end organs are activated equally and if there is no cross striolar inhibition between utricular fibers. However, such an inhibition (Uchino et al. 1999) may lead to an even smaller contribution of the utricles, but this cannot be resolved with the current data.

Variable nystagmus patterns

On the basis of our observation that during the two different stimulation paradigms the subjects exhibit similar OT patterns, we conclude that sustained GVS steps with amplitudes of 2 mA constitute a stimulus that is similar to an aVOR around a combined roll-yaw axis with initial step amplitudes ranging from 4 to 12°/s. We measured a torsional SPV gain of 0.22 at these stimulation levels. This value is significantly smaller ($P < 0.05$, t-test) than the torsional VOR gain of 0.37 reported earlier at higher angular velocities of 37.5°/s (Tweed et al. 1994b). In contrast, the gain of 0.39 of the corrected OT is comparable to known values for the gain of the torsional VOR (Seidman et al. 1994; Tweed et al. 1994b). The mechanism that may lead to a decreased SPV gain is best illustrated in the left OT plot of subject AH (Fig. 4). During the first 10 s of stimulation, only three nystagmus beats were detected. Without these quick phases the OT would theoretically show a pure low-pass response with a saturated period after about 6 s. Once saturation is reached, the derivative of this theoretical OT, i.e., the SPV, asymptotically approaches zero. If we calculated the SPV gain only for the saturated period of the theoretical OT, it would approach zero. In contrast, subject SG seems to have a totally different nystagmus pattern. His more frequently triggered quick phases keep the OT from becoming saturated and thus the SPV gain always remains different from zero. There are even cases where both patterns can be observed in the same subject or patient (APPENDIX, Fig. 5). The data from Fig. 5 clearly show that without nystagmus the SPV gain approaches zero. In contrast, after quick phases with high amplitudes, e.g., after blinks, the SPV showed significantly increased values compared with the SPV following “normal” nystagmus beats.

These observations lead to the conclusion that the SPV gain of the torsional VOR is inherently related to both the size and the frequency of the quick phases. It is thus dependent on nystagmus intensity, which is the product of mean quick phase
characteristic with decreasing values at smaller stimulus amplitudes (Peterka 1992). Since the crucial difference between the two methods of calculating the gain is whether or not the effects of quick phases are eliminated, we conclude that the nonlinear characteristics of the SPV gain of the torsional VOR may be the result of a nonlinear nystagmus processing rather than a nonlinearity in, e.g., the direct or the neural integrator pathway of the torsional VOR (Robinson 1981; Seidman et al. 1994).

With this in mind, it seems plausible to attribute the smaller torsional SPV gain to a nystagmus pattern that is less compensatory at the used slow head rotations. Additionally, the nystagmus pattern may vary from subject to subject and thus lead to the observed interindividual variability of OT patterns. Furthermore, a variable nystagmus pattern is suspected to have a strong effect on the phase of the SPV during dynamic stimulations (Galiana 1991). According to previously published data (Kleine et al. 1999), subjects stimulated with sinusoidal GVS indeed exhibit a torsional SPV phase with a considerable amount of variability.

**Nystagmus threshold**

In the present study we developed a new method of calculating the OT from artificial landmarks on the sclera. This method provided torsional data with a high signal-to-noise ratio. In spite of using an inexpensive camera, we were able to detect even small quick phase amplitudes down to 0.06°, which would have gone undetected if we had used a cross-correlation of irl landmarks. In the left plot of Fig. 2, for example, three of four nystagmus beats are hidden by the high noise level in the OT trace obtained from irl landmark detection. Hence, a meaningful measure for, e.g., the nystagmus intensity or a nystagmus threshold, can be given only on the basis of a method that ensures that all or at least the majority of the occurring quick phases can be discriminated from the underlying noise. In this context, it becomes clear that the concept of individually variable thresholds for nystagmic OT responses to GVS (Zink et al. 1997, 1998) must be reconsidered.

**Blink-triggered quick phases**

Our findings suggest that blinks are able to trigger torsional quick phases when the SCC afferents are stimulated either by head rotations in the torsional plane or by transmastoidially applied currents. However, blinks do not have any effect during ocular counter-roll induced by a static head tilt of 15° around the nasooccipital axis (unpublished observation). Thus blink-triggered torsional quick phases resemble torsional corrections during saccadic eye movements, which are elicited by nystagmus threshold, can be given only on the basis of a method that ensures that all or at least the majority of the occurring quick phases can be discriminated from the underlying noise. In this context, it becomes clear that the concept of individually variable thresholds for nystagmic OT responses to GVS (Zink et al. 1997, 1998) must be reconsidered.

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The pathways responsible for these effects might be common projections of the extraocular muscle and levator palpebrae efferents to rostral mesencephalic regions (Horn et al. 2000). A blink-triggered torsional quick phase could be physiologically meaningful, since rapid reorientation after a blink can be crucial during head movements. One possible strategy would be to generate a quick phase, e.g., at the time the eyelid is opened. Then the following compensatory slow phase keeps the image stable on the retina. In addition, the saccadic visual suppression mechanism may be used by the blink system during the time the eyelid is closed (Ridder and Tomlinson 1993).

Galvanic sensitivity of vestibular afferents

In an earlier study (Schneider et al. 2000a) we estimated the effect of GVS on vestibular afferents. We calculated that a current of 1 mA triggers an increased firing rate of 0.76 Hz. There was no significant difference at a 5% level of confidence (t-test) between this value and the value of 1 Hz/mA estimated in the present study from the SPV. To calculate this sensitivity we have used the approximations outlined in Fig. 1 to obtain the simple equations given in RESULTS section. In view of the departure of these approximations from the true anatomical SCC orientations (Blanks et al. 1975; Rabbit 1999), this value can be regarded only as a very rough estimate of the magnitude of the afferent sensitivity to transmastoidally applied currents. An additional error, which might have been introduced by an inaccurately estimated cupular time constant, can be rejected, since the SPV slopes were not significantly different for the two stimulation conditions.

In a further approximation we considered only regular afferents, although it is known that irregular afferents contribute to the horizontal VOR (Angelaki and Perachio 1993) with a sixfold increased galvanic sensitivity compared with the sensitivity of regular afferents (Goldberg et al. 1984). Angelaki and Perachio (1993) showed that functional ablation of irregular afferents leads to a significant decrease in the gain of the horizontal VOR if angular velocity steps were applied. A change in horizontal VOR parameters, however, has not been observed during sinusoidal stimulations with frequencies of 0.5–4 Hz (Angelaki and Perachio 1993; Minor and Goldberg 1991). A tentative explanation of these rather contradictory observations was that regular afferents drive the direct pathway of the horizontal VOR, while irregular afferents have an influence on the indirect pathway of the velocity storage system, which (by resembling the characteristics of a low-pass filter) artificially increases the cupular time constant (Angelaki and Perachio 1993). Since velocity storage has not been observed for the torsional VOR (Tweed et al. 1994a), we believe that it is justified to disregard irregular afferents in our approach to estimate the galvanic sensitivity from torsional eye movement data.

Conclusion

Our study shows that the ocular torsion-related effects of constant galvanic vestibular stimulation with tolerable currents are similar to an accelerated head rotation at small amplitudes, which stimulates all semicircular canal afferents. The applied method of corrected ocular torsion provides comparable results showing a similar time course for all subjects even though the raw ocular torsion data may differ markedly. Thus the present study may be a basis for the use of galvanic stimulation at the mastoid level as a tool for the clinical examination of vestibular function.

APPENDIX

Nystagmus compensation

The major problem in the analysis of ocular torsion data obtained from, e.g., head rotations with small amplitudes is the interindividual variability of eye movement patterns; some subjects exhibit rather tonic responses, some show a pronounced nystagmic reaction, while others respond with an intermediate pattern of a tonic component on which nystagmus is superimposed. There are cases in which the two extremes can be observed in the same subject (Fig. 5).

In the presence of such variable nystagmus patterns, the estimation of reliable VOR parameters like gains and time constants can be difficult. If SPV and the tonic OT alone were used in the analysis of the original OT data from Fig. 5, different results would have been obtained for the two stimulation polarities. While the SPV for the first stimulation period is not significantly different from zero, a considerable amount of tonic OT response can be observed. In contrast, during the second stimulation period, the SPV is increased and the tonic OT is decreased. However, after artificial nystagmus elimination, the thus corrected OT becomes similar to original OT traces in which no nystagmus beats are apparent (compare 1st and 2nd stimulation period in Fig. 5, A and D). Hence the “corrected OT” is the OT expected in the absence of nystagmus.

This algorithm, which we first used for the analysis of sinusoidally modulated torsional eye movements (Schneider et al. 2000a), is similar to a nystagmus analysis method introduced by Rey and Galiana (1993). Both methods are model-based approaches for estimating the gain and the time constant of the neural integrator pathway of the VOR (Robinson 1981). While Rey and Galiana (1993) added nystagmus bursts and afferent activation to the input of the neural integrator and minimized the error between the predicted and the original eye movements, our method adds inverse nystagmus to the original OT and minimizes the error between the thus corrected OT and a low-pass filtered version of the afferent activation.

The resulting corrected OT might be confused with slow cumulative eye position, which it is not. Both the slow cumulative eye position and our corrected OT are similar in that they eliminate quick phases from eye position recordings. However, while slow cumulative eye position assumes a linear slow phase trajectory, our method takes into account the true exponential nature of the shapes of torsional slow phase trajectories (Schneider et al. 2000a) with their time constant of about 2 s (Seidman et al. 1994). Slow cumulative eye position algorithms were initially developed to analyze horizontal and vertical eye movements with low-pass dynamics of typically 30 s. Had we used such an algorithm for the analysis of the original OT for the second stimulation period (Fig. 5A), we would have overestimated the VOR gain. It should be noted that the simple model used in this approach does not predict the whole range of torsional VOR eye movements. It is more likely that the accuracy of this algorithm might be decreased by torsional fluctuations and the imperfect control of torsional eye movements (Ferman et al. 1987; Straumann et al. 1996).

Videooculography

In the present study we applied infrared absorbing markers to the sclera (Clarke et al. 1999). In previous videooculography studies of galvanically induced torsional eye movements, cross-correlation algorithms were used to calculate the OT either from irl segments (Schneider et al. 2000a; Zink et al. 1997, 1998) or from scleral markers (Kleine et al. 1999). Since these algorithms rely on an exact
detection of the pupil center, the noise generated by the pupil approxima-
tion is also reflected in the OT data. We calculated the angles of OT
directly from two landmarks similar to a method introduced in an
earlier study (Young et al. 1981). In that study natural iris landmarks
were detected by template matching. Due to the high contrast between
the applied artificial landmarks and the white sclera, we were able to
replace the template matching with a simple center-of-intensity calcu-
lation of marker pixels. Since the center of intensity is nothing else
but a weighted mean, its use has several advantages over the use of a
template matching algorithm. Template matching increases the com-
puting time with orders of \(N \cdot \log N\) to \(N^2\) compared with an order of
\(N\) for the weighted mean. The resulting error of a weighted mean
degrees with an order of \(1/N^2\) (Eqs. A1 and A2), while a template
matching result remains at a pixel resolution (Wagner and Galiana
1992), which can be improved only by additional computationally
intensive prerequisites, such as oversampling with a bilinear interpo-
lation or fitting a paraboloid to, e.g., the cross-correlation or matching
function.

In the first step, the image processing software calculated a rough
estimate of the pupil position by detecting pupil pixels with a thresh-
hold operation (Fig. 2, left column). Relative to this position, two
regions of interest in the vicinity of the expected marker positions
were defined. In these regions the pixel intensities were blurred with
a floating nine-point mean filter and then thresholded with an offset
value relative to the darkest pixels. We tested the performance of a
nine-point median filter and a nine-point mean filter, but only the
mean filter considerably decreased the data noise compared with the
unfiltered image. Only the \(N\) remaining dark pixels entered a center-
of-intensity calculation (Eq. A1) from which the marker coordinates
were obtained. If the inverted intensity and the \(x\)-coordinate of the
pixel \(i\) are given with \(I_i\) and \(x_i\), respectively, the \(x\)-coordinate \(m_x\) of a
marker can be calculated with

\[
m_x = \frac{\sum_{i=1}^{N} I_i \cdot x_i}{\sum_{i=1}^{N} I_i}\)  \hspace{1cm} (A1)
\]

Under the assumption that the spatial resolution \(r_x\) of the camera
amounts to 1 pixel and that the error \(s\) of the pixel intensity corre-
sponds to the image noise (defined as the SD of, e.g., the pupil pixel
intensities), the error \(e_x\) of \(m_x\) can be calculated from the derivatives
of Eq. A1 with

\[
e_x^2 = \left( r_x \cdot \sum_{j=1}^{N} d m_i / d x_i \right)^2 \left( \sum_{j=1}^{N} d m_j / d I_j \right)^2
\]

\[
= \left[ s^2 \cdot \sum_{i=1}^{N} (x_i - m_x)^2 + \sum_{i=1}^{N} I_i^2 \right] / \left( \sum_{i=1}^{N} I_i^2 \right)^2
\]  \hspace{1cm} (A2)

Using all the video images recorded in this study, we thus obtained a
mean resolution of the marker coordinates of \(0.13 \pm 0.01^\circ\). From continuous nystagmus-free portions of the torsional data, the mean OT noise was measured to be
\(0.04^\circ\). This empirical value is on the order of the error, which we
deduced with Eq. A2. The mean of the first quartile of all detected
quick phase amplitudes was \(0.18 \pm 0.05^\circ\). For the minimally detected
quick phase of \(0.06^\circ\), the signal-to-noise ratio of the video system
used approaches 1. Thus it was possible to discriminate even small
nystagmus beats with amplitudes below \(0.1^\circ\) from the underlying
noise.

We addressed the question of whether this newly developed algo-
rithm is better suited for an analysis of GVS-induced OT than the
cross-correlation algorithm previously used for this purpose (Schnei-
der et al. 2000a; Zink et al. 1997, 1998). We therefore analyzed the
video images shown in Fig. 2 with both a cross-correlation of 16 iral
segments and a center-of-intensity detection of the scleral markers.

The OT noise was \(0.017\) and \(0.14^\circ\) for the center-of-intensity and the
cross-correlation methods, respectively. The difference in the quality
of the data delivered by the two methods is illustrated in the left plot
of Fig. 2.

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