Objective: To characterize the horizontal angular vestibulo-ocular reflex using a new motorized head impulse rotator and electro-oculography technique.

Design: Prospective case-control study.

Participants: We included 22 healthy volunteers with unpredictable, horizontal motorized head impulses with a mean velocity of 170°/s and a mean acceleration of 1550°/s². We recorded head and eye position and calculated gain, asymmetry, and latency of the vestibulo-ocular reflex. All subjects underwent testing twice while viewing a far (140 cm) target to evaluate the repeatability of the measurement. In addition, 8 of these subjects underwent testing while viewing a near (15 cm) target. We reported findings as mean±SD.

Results: The mean gain during the 30-millisecond interval before peak head velocity and during the interval when head velocity ranged from 100°/s to 120°/s was 1.08±0.10. The mean asymmetry in gain between sides was 3.7%±2.8%, and the mean latency of the vestibulo-ocular reflex was 3.4±6.3 milliseconds. There was a statistically significant correlation between consecutive gain measurements for each subject (r=0.59; P=.004). The mean gain for the near target was 1.26±0.10 and was significantly higher than that for the far target (P=.002).

Conclusions: The vestibulo-ocular reflex measurements using our novel system are comparable to those achieved using other techniques. These results suggest that a motorized head impulse rotator with electro-oculography allows reliable and fast measurement of the vestibulo-ocular reflex. In addition, the method is safe, repeatable, and thus could be a useful tool in the clinical assessment of the vestibulo-ocular reflex.

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The vestibulo-ocular reflex maintains image stability on the retina by providing compensatory eye movements during head movements. Thus, vestibular function can be most naturally measured by calculating input-output characteristics of eye and simultaneous head movements. There is a large asymmetry between excitatory and inhibitory responses of the vestibular hair cells (Ewald’s second law), which makes it possible to measure each side separately by moving in only 1 direction at a time. The head impulse (or thrust test) relies on this physiological background, and it has been used clinically and experimentally. In clinical examinations, the main interest is in the occurrence of refixation saccades induced by dysfunction of the horizontal angular vestibulo-ocular reflex. The identification of refixation saccades by clinical observation only can be difficult because identification is based on the subjective recognition of a fast corrective eye movement. More precise quantification of the horizontal vestibulo-ocular reflex is based on gain, latency, and asymmetry calculation from the eye and head movement signals.

The manual head impulse test, which uses magnetic search coils to measure eye movements, is invasive and demanding in the clinical setting. Therefore, it has remained available for only a limited number of patients and vestibular laboratories. The stimulus velocities of manual head thrusts may be highly variable between experimenters. Tabak and Collewijn introduced helmet-driven, motorized head movements instead of manual stimuli to homogenize the intensity of the head thrust stimulus. They achieved well-controlled transient horizontal head impulses with a mean acceleration of 770°/s² and velocities of 50% to 100% during their analysis window. This velocity range is close to the velocity saturation seen in patients with...
vestibular complaints, which might limit the usefulness of the equipment. We constructed our head impulse rotator to accomplish stimulation magnitudes well above this velocity saturation range and to better control the stimulus intensity.

We chose electro-oculography to record eye movements because of its easy setup and common use in vestibular laboratories. Herein we show that our motorized head thrust test gives reliable estimates of the horizontal vestibulo-ocular reflex.

**METHODS**

**SUBJECTS**

We studied 22 volunteers (5 men and 17 women) with a mean age of 42 (range, 27-59) years; no history of vestibular, ocular, motor, or neurological abnormalities; and normal or corrected vision. All subjects gave informed consent for the vestibulo-ocular reflex recording through a protocol approved by the Ethics Committee of the Helsinki University Central Hospital.

**APPARATUS**

Passive, unpredictable horizontal head-on-body rotations were generated by a motor and gear combination (DC motor GR 63 × 25 and planetary gear PLG 52.0; Dunkermotoren Alcatal SEL AG, Bonndorf, Germany). The motor and gear were fixed to the rigid backrest of a chair, with the axle upward and a rotating plate attached to the axle. The rotations were delivered to a tightly fastened leather helmet worn by the seated subjects (Figure 1). The helmet could be individually fitted by tightening plastic belts from an industrial worker’s safety helmet in the horizontal and oblique planes. Two pushrods from the rotating plate on the gear output axle were connected to the joints on both sides of the helmet. The turning angle of the rotating plate was mechanically limited to ±30° for safety reasons. In addition to the 2 pushrods, the top of the helmet was stabilized with a rotating joint to a supporting bar, which eliminated anteroposterior movement of the head. Two additional wooden supporting rods were attached to the bar and the chair to alleviate unnecessary lateral movement.

The desired short constant torque impulse was obtained by driving the motor with a pulse of increasing voltage. The voltage waveform was fed to a motor driver (LA5600 linear drive amplifier, Electro-Craft Corporation Motor & Control System Division of Robbins & Myers, Minneapolis, Minn). The proper pulse waveform was determined experimentally to produce an approximately linear velocity increase during the first 120 milliseconds with constant acceleration (up to 2000°/s²) for each impulse. Active braking was obtained by applying a reversed driving voltage to the motor. The return to the starting position was accomplished by driving the motor at a slower pace. The motor voltage was switched off with an optical center position detector when the central position was approached.

**RECORDING SYSTEM**

Head position was measured with a rotation-angle sensor (type CP-2UT; Midori Precisions Co, Ltd, Tokyo, Japan), which was directly attached to the helmet. The noise velocity of the sensor was less than 0.1%/s.

The eye position was monitored via conventional electro-oculography. Two active electrodes were attached to the lateral canthi of the eyes and a second electrode was mounted to the forehead. The electro-oculographic signal was amplified and low-pass filtered with a cutoff frequency of 30 Hz before the analog-to-digital conversion. The eye and head movement signals were recorded with a sampling frequency of 400 Hz and a 16-bit resolution. Before the analysis, the electro-oculographic signal was further low-pass filtered with a cutoff frequency of 10 Hz. The noise velocity of the electro-oculographic signals was less than 5°/s. Eye movement was calibrated by recording horizontal saccades of 20°.

**PROTOCOL**

The subject was seated upright and was instructed to fixate at the light-emitting diode target, located 140 cm on the midline and at eye level. The head was positioned comfortably in an approximately horizontal plane within the helmet, but we made no attempt to measure Reid’s line. While the subject fixated at the light-emitting diode target, the head of the subject was rotated in the horizontal plane. The movements were randomized in direction and in time interval between impulses (range, 1.0-1.4 seconds). These passive transient head rotations had a mean ± SD acceleration of 1550°/s² ± 240°/s², mean ± SD peak head velocity of 170°/s ± 27°/s, and mean ± SD amplitude of 21° ± 3°. The average duration from the beginning of the head impulse to the peak velocity was 120 milliseconds. Each test lasted 80 seconds and consisted of 23 impulses in each direction (left and right).

All subjects underwent testing twice, with calibration before each test, to evaluate the repeatability of the measurement. Eight subjects underwent additional testing with a target distance of 15 cm to measure the influence of the target distance to the gain.

**ANALYSIS**

The processed eye and head movement signals were fed into a data analysis program developed by one of us (A.A.M.) running under the LabView program, version 7.1 (National Instruments, Austin, Tex). Data with prominent noise or artifacts that commenced before the onset of the head movement were manually discarded from the analysis. Impulses with velocities less than 100°/s and with eye velocities larger than 20°/s at the beginning of the head movement were excluded. The onset of head movement was determined as the time when head velocity reached 10°/s.

The vestibulo-ocular reflex gain was calculated by dividing the eye velocity by the inverted head velocity. The individual results were the mean gain values of the head impulses performed to the right and left sides. The velocity gain was calculated in the following 2 ranges: during the 30-millisecond period before peak head velocity and in the period when head velocity ranged from 100°/s to 120°/s, thus achieving uniform stimulus velocities for all subjects. The gain values were also
normalized for the viewing distance of 140 cm according to the method of Mansson and Vesterhauge.10

To quantify the asymmetry of the response to left and right rotations, the asymmetry was defined by the following equation:

$$\text{Asymmetry} = \frac{|\text{Gain Right} - \text{Gain Left}|}{\text{Gain Right} + \text{Gain Left}} \times 100\%.$$  

Latency, the delay between head and compensatory eye movements, was calculated as the time difference in milliseconds between the head and eye reaching the threshold velocity of 10°/s.

Statistical calculations for the collected data of gain, latency, and asymmetry were performed using SPSS statistical software, version 11.0 (SPSS Inc, Chicago, Ill). We used the non-parametric Pearson rank correlation test to compare the gain values, measured from 2 different parts of the head impulse curve. Intraclass correlation coefficients (r) and probabilities (P) were computed to evaluate the repeatability of the test. The gains at different target distances were compared with the t test for paired samples. Unless otherwise indicated, data are expressed as mean±SD.

**RESULTS**

Recording examples are shown in Figure 2 and Figure 3 for a healthy subject and a patient with idiopathic total loss of bilateral vestibular function (no caloric responses), respectively. The compensatory eye movements match closely with head movements in the healthy subject, whereas in the patient with vestibular abnormality the eye movements differ considerably from the head movements.

The mean gain values are shown in detail in Table 1. The gains measured during different analysis windows did not differ significantly (P>.05).† Indicates within 30 milliseconds before peak head velocity.‡ Indicates head velocity range of 100°/s to 120°/s.

The mean gain values at 2 different target distances are shown in Table 2. The mean gain was significantly higher for the target distance of 15 cm (P=.002). There was no significant difference between the sexes in gain or in latency.

The necessity for physiological measurement of the vestibulo-ocular reflex in clinical practice is inevitable. To our knowledge, this is the first construction that uses the motorized head impulse rotator with an electro-
oculographic recording to evaluate the horizontal vestibulo-ocular reflex. We achieved results comparable to those of the magnetic search coil techniques used previously. 5-7 In addition, our method is noninvasive, safe, repeatable, and easy to perform for the operator and the subject. Our method demands no special effort from the patients, and it allows fast measurement of horizontal vestibulo-ocular reflex function in a clinical setting.

We did not make any comparison with manual impulses, but one can assume that the stimulus intensity is better controlled with motorized than with manual impulses. Indeed, Tabak et al 6 found that motorized impulses resulted in more uniform acceleration than manual ones, although the results agreed in general. Furthermore, the velocity range of manual impulses varies considerably, from less than 100°/s to 400°/s in different studies. 8,11-14 Thus, the magnitude of manual impulses is highly dependent on the individual experimenter, which must be taken into account when comparing the results of different studies. Accordingly, a more standardized approach using a precise stimulus should be superior.

Our equipment ensures that measurement of horizontal vestibulo-ocular reflex occurs within the dynamic range of normal head movements. 5,15 The motor can be driven with different stimulus intensity and duration, which makes it possible to study different velocity and acceleration ranges. Tabak and Collewijn 1,2 and Tabak et al 6,7 first used the helmet-driven torque motor and magnetic sensor coil technique to evaluate the horizontal vestibulo-ocular reflex. Their stimulus intensities during the time window of 90 milliseconds in the analysis were close to the eye velocity saturation of 50% to 75% seen in patients with vestibular abnormalities; thus, the difference in the gain between healthy subjects and patients was smaller, diminishing the usefulness of the test. 8 The mean stimulation magnitude of 170°/s used in our study was well above this saturation range, which should make it possible to distinguish between normal and even partial lesions in the horizontal vestibulo-ocular reflex. Roy and Tomlinson 16 compared the velocity ranges of manual head thrusts and found that velocities up to 200°/s produced the most repeatable results. Our study is in agreement with that finding. All of our subjects underwent testing twice to evaluate the repeatability of the measurement, and the correlation between the 2 consecutive measurements was high (P = .004) with an average 6% variance in gain within subjects.

We chose conventional electro-oculography to record eye movements owing to its noninvasive and easy setup with surface electrodes. The disadvantage of electro-oculography is its low resolution of approximately 1° and its relatively high-velocity noise level of less than 5% in our measurement. Careful placement was required to minimize unwanted movement of the electrodes and leads during testing. Filtering of the eye movement signal has to be effective to eliminate the high-frequency noise. Therefore, a cutoff frequency of 10 Hz was applied to the signal before conversion to angular velocity. Impulses with prominent noise were discarded from the analysis according to the criteria shown in the "Recording System" subsection of the "Methods" section. This issue was examined in detail using a subset of subjects, and it was determined that the removal of individual impulses had a negligible effect on the results. This finding is likely owing to the fact that averaging a group of impulses to each side effectively reduces the impact of a single impulse. Altogether, traditional electro-oculography seems to be effective in recording horizontal vestibulo-ocular reflex.

The horizontal vestibulo-ocular reflex gain for responses to brief, unpredictable, high-velocity impulses is close to 1.0, which is analogous to our gain values 8,11-12,17,18 The mean velocity gain within the 30-millisecond interval before the peak head velocity was 1.08 ± 0.10, and the normal range derived from this is 0.88 to 1.28 (mean ± 2 SDs). If we normalize the gain for the target distance of 1.40 cm, we obtain a mean gain of 1.02 (normal range, 0.84-1.20), which is close to the ideal of unity. Because of individual varying factors such as neck stiffness during head impulses or the weight of the head, the final head velocity in a group of subjects is never uniform, despite similar stimulus intensity delivered to the helmet. Therefore, we also analyzed the gain in the head velocity range of 100% to 120% to achieve uniform stimulus for all subjects. The mean gain in this range was 1.08 ± 0.10, which was the same as that measured during the 30-millisecond interval before peak head velocity. Thus, it appears that a small variation in the stimulus does not adversely affect the results in healthy subjects.

We calculated directional asymmetry in gain for healthy subjects. The asymmetry of 3.7% ± 2.8% in our work agrees well with the following normal values presented in previous studies: 5.6% by Schmid-Priscoveanu et al 14, 4% ± 2% by Allison et al, 12 and 5.8% by Park et al. 19 Our normative range (mean ± 2 SD) for asymmetry remained within 10%, which makes it a promising variable for the detection of unilateral weakness.

The mean delay between the head movement and the compensatory eye movement evoked by our stimulus was 3.4 ± 0.6 milliseconds. This value is smaller but comparable to the latency measured with passive head-on-body rotation by Aw et al 18 (7.5 ± 2.9 milliseconds) and with whole-body rotations by Crane and Demer 20 (7-10 milliseconds). Furthermore, the value is consistent with the latency reported with the helmet technique. 5,21 Helmet slippage should increase latency, and it should consequently decrease gain in our test. Therefore, it seems unlikely that any significant uncoiling of the helmet and head occurred, because our latency was shorter than reported and the mean gain was 2% greater than the ideal. The relatively wide range of our latency could be partly explained by the electro-oculography recording technique, in which the accuracy is more vulnerable to noise. The magnetic search coil technique should be advantageous, although Aw et al 18 emphasized the importance of tight fixation of the head and eye coils during the measurements with high acceleration to avoid bias.

Lasker et al 13 reported a significant increase in vestibulo-ocular reflex gain in response to high-velocity head rotations during near-target viewing (15 cm) compared with far-target viewing (124 cm), as a result of vergence-mediated modulation of the reflex. Their mean gains were 1.25 ± 0.08 vs 1.01 ± 0.06, respectively. Crane and Demer 20 found greater horizontal vestibulo-ocular reflex gain with near targets than with remote targets. In our study,
8 subjects underwent testing with both target distances of 140 and 15 cm, and our results were consistent with those of the previous work.

In conclusion, the motorized head impulse rotator with electrotoculography is a reliable and fast method to measure the horizontal vestibulo-ocular reflex. Measurements in patients with vestibular abnormalities using a motorized rotator are currently under way to evaluate the clinical importance of this novel method.

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