Assessment of Ocular Counterroll during Head Tilt Using Binocular Video Oculography

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PURPOSE. According to recent literature, the presence and the amount of true compensatory ocular counterroll is still debatable. The purpose of the current study was to assess compensatory counterroll in response to lateral head tilt using a new noninvasive recording technique, and, furthermore, to find out whether the amount of counterroll is influenced by the presence or absence of spatial orientation.

METHODS. Eye movement recordings were performed using the infrared three-dimensional video oculography (3D-VOG) technique. Objective cycloposition of five healthy individuals was measured in presumed primary position and in head tilt positions of 15°, 30°, and 45° to the right and left. The same paradigm was performed under three viewing conditions: binocularly without spatial orientation and both binocularly and monocularly with spatial orientation.

RESULTS. A consistent ocular counterroll corresponding to the amount of head tilt was observed in all subjects. Maximum torsional amplitude was 10° at a 45° head tilt. The relative amount of compensation ranged between 15% and 22% of the actual head tilt, decreasing with increasing head tilt. Compensatory counterroll and torsional conjugacy between both eyes revealed minor differences between the experimental paradigms. Incomplete cycloductions were recorded in different head-tilt positions after head tilt was detected in all subjects, regardless of the stimulus.

CONCLUSIONS. A consistent compensatory ocular counterroll was demonstrated in response to static lateral tilting of the head in healthy individuals. The amplitude of counterroll and the gain of compensatory cycloversion were higher than has been generally reported. Infrared 3D-VOG technique was a reliable and comfortable method for the assessment of ocular counterroll. It can be considered to be a promising tool for advanced evaluation of disturbances of the oblique eye muscles. (Invest Ophthalmol Vis Sci. 2002;43:662–667)

For several decades, the question has been debated of whether and to what extent tilting of the head toward the shoulder induces a real counterroll of the eyes to compensate for the retinal image rotation. Accurate knowledge of the phenomenon of compensatory counterroll is of clinical importance when interpreting results of the Bilschowsky head tilt test (BHTT) in search of disorders of the oblique eye muscles.

The outcome of the BHTT is called positive (i.e., pathologic) if a vertical deviation is induced when the head is tilted laterally. According to Hofmann and Bielschowsky,¹ the upgaze movement of the ipsilateral eye is caused by a limitation of the intended compensatory incycloduction that is due, for example, to paresis of the superior oblique muscle. Instead, the superior rectus muscle is activated to compensate for the deficiency, using its incyclotorsional capacity. The upgaze movement, however, is stronger than the incycloduction, thus leading to a vertical deviation.

To obtain further reliable information on this subject, it was the purpose of this study to objectively evaluate ocular cycloduction induced by the BHTT in normal subjects, using a new device for recording of eye movements. Furthermore, the intent was to find out whether the amount of counterroll is influenced by different viewing conditions, such as binocular versus monocular fixation and fixation with versus without visual spatial orientation.

METHODS

Subjects

This research adhered to the tenets of the Declaration of Helsinki. Informed consent was obtained from all individuals after the nature and possible consequences of the study were explained. Five healthy individuals were enrolled in the study, three men and two women. Mean age was 47 years (range, 35–60). No individual had a history or signs of neurologic disorders or eye movement disturbances. All individuals underwent a full ophthalmic and orthoptic investigation, including the measurement of the angle of squint in nine directions of gaze under full dissociation, using the Harms’ tangent screen.²,³ as further described by us in a prior study.⁴ Ocular dominance was tested by an objective confrontation method. No abnormality of ocular functions and ocular motility was detected in the five subjects.

Infrared Video Oculography

Eye position and movements including ocular torsion wasbinocularly recorded in different head-tilt positions by means of a three-dimensional video-oculography (3D-VOG) technique. A commercially available system (Senso Motoric Instruments GmbH, Teltow, Germany) was used. The term three-dimensional is used for the three rotary degrees of freedom of the eye: horizontal, vertical, and torsional.

Video images of both eyes were acquired by two miniaturized charge-coupled device (CCD) video cameras mounted in a light-occluding mask with a glass window in the front. For each camera, three infrared LED sources with a wavelength of 920 nm and an intensity of less than 1 mW/cm² provided the necessary illumination of each eye. Sampling frequency for torsional movements was 25 Hz and for horizontal and vertical movements 50 Hz. The video signals of both eyes were recorded on magnetic tape for further off-line analysis. Spatial resolution of the system was 439 Kilopixels. For image processing, the monochrome image was digitized with 256 gray levels, corresponding to 8-bit resolution (for further information about the analysis technique, see the Data Analysis section, to follow). The 95% confidence interval (CI) for ocular torsion was approximately ±0.1°. Maximum deviation of torsion linearity was ±1.4% at a range of ±20°. A more
detailed description of technical data is provided in the instruction manual of the recording device and in studies comparing the accuracy of the system with other recording techniques.5,6

Because a stable position of the cameras and the subject’s head during the recording is mandatory to obtain reliable data, any head movement other than sideward tilting was restricted by a specially constructed tiltable chin rest, including an individually adjustable bite bar with a scale indicating the amount of head tilt in degrees (Fig. 1). The chin rest was firmly mounted to a frame that yielded a comfortable sitting position for the subject. Care was taken to adjust chair and chin bar according to the individual to avoid any inclination of the head and to assure that the gaze would be in a straight-ahead direction.

Paradigms

During the experiments, the study subjects were instructed to fix a stimulus that was projected onto a translucent screen by means of a video projector mounted behind the screen. The projector was connected to a computer, and the stimulus was created and displayed using a commercial software package (Power Point; Microsoft Corp., Redmond, WA). The subject sat with the head at 150-cm distance from the screen.

To test for the influence of spatial clues and the difference between monocular and binocular fixation, the eye movements were recorded under three different viewing conditions: binocular fixation without spatial orientation (test 1), binocular fixation with spatial orientation (test 2), and monocular fixation with spatial orientation (test 3).

During test 1, no clues for horizontal orientation were visible to the subject, because of the complete darkness in the investigating room. The fixation target consisted of two yellow concentric circles on a black background. During tests 2 and 3, a photographic picture of a Swedish historical building (Gripsholm castle) was presented, with a red dot in the center serving as fixation target. The purpose of this picture was the presentation of multiple horizontal and vertical clues, and an additional grid pattern was superimposed on the photograph. For test 3, the dominant eye was selected for fixation, and the fellow eye was occluded. To avoid interference by unnecessary visual input beyond the projected stimulus, the redundant part of the mask window was covered by a paper frame (Fig. 1).

Each recording started with the individual’s head in a straight upright position (0°) and the eyes in the reference position. This was followed by a stepwise head tilt to the positions of 15°, 30°, and 45° to the right and then back to the head-upright position. From there, the head was tilted correspondingly to the left and was eventually reset to an upright position with the eyes in the reference position. The total duration of one test protocol was approximately 2 minutes, and the interval between each tilting step was approximately 10 seconds. The subject was instructed to keep the gaze on the target during the whole test. For purposes of analysis, the time when each head tilt was completed was noted in the study protocol.

Definitions

In the present report, cyclovergence is used to describe both the conjugated torsional movement of the two eyes simultaneously and the cycloposition reached after such a movement. Similarly, cycloduction is used to describe the monocular torsional movement and the cycloposition reached after such a movement. Cycloversion is calculated as the difference between the left and right eye positions (LE − RE), whereas cyclovergence is calculated according to the formula (LE + RE)/2 to describe the mean eye position. The direction of torsional eye movements (i.e., clockwise and counterclockwise) was defined as seen from the subject’s perspective.

Data Analysis

Using the software provided with the 3D-VOG system, the video frames were digitized, calibrated, and transformed into ASCII format for the six channels (horizontal, vertical, and torsional channels of both right and left eye). Horizontal and vertical positions were evaluated by means of the black-pupil technique—that is, the geometrical calculation of the center of lowest infrared reflection (center of pupil) using the Fick coordinate system. Ocular cycloduction was assessed by calculation of the angular displacement of position of a defined iris segment. This was achieved by extraction of gray levels of the defined iris segment (profile) and subsequent correlation of the profile with that of the neighboring segments for each video frame. The concordance between the initially selected reference profile and that of the same iris segment of each consecutive frame throughout the recording was computed by the software and called torsion quality, a decimal value ranging between 0.0 (no concordance) and 1.0 (maximum concordance). According to the instruction manual, only data with a torsion quality of 0.3 and better should be considered for evaluation, because a quality value below 0.3 does not guarantee correct evalua-
tion of cycloduction. To further minimize the risk of false data, only frames with torsion quality higher than 0.5 were included in the analysis of this study. Thus, data containing artifacts such as blinks were identified and removed. Every individual's average cycloductional amplitude at each of the nine different head positions was assessed by averaging the cycloduction during 5 seconds of stable head position at each step.

RESULTS

Good torsion quality with low noise was found in all subjects. Overall, less than 4% of the recorded data had a quality level of 0.5 or below and, according to the study protocol, the data were excluded from the analysis.

Cycloduction

The raw data of the torsional eye movement recordings of all individuals in each test situation are illustrated by the graphs in Figure 2 and one of the tracings at an expanded time scale in Figure 3. In response to the stepwise tilting of the head, all subjects showed a consistent ocular counterroll of both eyes that increased with the head tilt, and no significant difference in the amount of ocular counterroll was seen between the data for tilting to the right or left. The maximum cycloductional amplitude evoked at 15° ranged between 2.3° and 3.6°. The corresponding readings at 30° head tilt ranged between 4.7° and 6.4° and those at 45° head tilt ranged between 5.4° and 7.4° (Table 1). Considering the residual amount of torsional amplitude at the end of each head tilt paradigm caused by the fact that the eyes did not return to the exact original cyclo- position (explained in the following section), the maximum cycloductional amplitude increased to 9.3° (Table 1).

Transient Change in Cycloduction

A consistent phenomenon detected in the recordings was a saccadelike rapid torsional eye movement in the same direc-
Conjugacy

The mean cycloductions in all five subjects are listed in Table 1. The difference of the mean cycloduction between the two eyes was less than 1° in all experiments, indicating generally good torsional conjugacy of the eyes during the two different viewing conditions (monocular and binocular) and the two different visual conditions (with and without spatial orientation). However, during test 1, in which no spatial clues were present, there was a tendency for consistent small disconjugacy during the first part when the head was tilted to the right. This disconjugacy corresponded to a larger amplitude of ocular counterroll of the left eye (excyclovergence) than of the right eye (incycloversion), thus inducing an excyclovergence that somewhat increased with the amount of head tilt (Table 1). A corresponding consistent phenomenon was not found in the second part of test 1 (head tilt to the left) nor in test 2 (spatial clues, binocular viewing) or test 3 (spatial clues, monocular viewing).

Cycloversion

The data of average cycloversion of the five volunteers are shown in Table 1 and illustrated in Figure 4. During the different paradigms, compensatory cycloversion ranged between 2.6° and 4.1° at 15° head tilt, between 5.1° and 6.4° at 30° head tilt, and between 6.3° and 8.3° at 45° head tilt. The three traces in Figure 4 suggest that the amount of counterroll in response to head tilt was similar under the three different viewing conditions and that there was no clinically significant difference between them.

Gain

The gain of the average counterroll was calculated as the ratio between the amplitude of counterroll and the amount of head tilt. The same data given in percentages represent the relative amount of compensation. The data are listed in Table 1 and illustrated in Figure 5. The relative amount of compensation ranged between 18% and 27% at 15° head tilt, between 17% and 21% at 30° head tilt, and between 14% and 18% at 45° head tilt. These data illustrate that the relative amount of compensatory counterroll was higher at a lower level of head tilt and that the compensatory response decreased with increasing tilt of the head. Compared with Figure 4, Figure 5 reveals that the relative amount of compensation was a more sensitive parameter than the amount of cycloversion. The graph in Figure 5 illustrates that the first tilting of the head, which was directed toward the right shoulder, evoked the largest relative cycloversional compensation during binocular viewing with spatial orientation (test 2), whereas the smallest compensation was observed during monocular viewing with spatial orientation (test 3). Testing during binocular viewing without spatial orientation (test 1) revealed an amount of torsional compensation less than in test 2 and more than in test 3. The second head tilt, which was directed toward the left shoulder evoked a larger compensation and minor differences between the different test conditions.

Table 1. Eye Position and Movements

<table>
<thead>
<tr>
<th>Head Position</th>
<th>Cycloposition</th>
<th>Cycloversion</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cycloposition</td>
<td>(RE + LE)/2</td>
<td></td>
</tr>
<tr>
<td>Upright</td>
<td>0.10</td>
<td>-0.05</td>
<td>21</td>
</tr>
<tr>
<td>15° Right</td>
<td>-2.97</td>
<td>-3.57</td>
<td>-3.20</td>
</tr>
<tr>
<td>30° Right</td>
<td>-5.12</td>
<td>-6.04</td>
<td>-5.51</td>
</tr>
<tr>
<td>45° Right</td>
<td>-6.29</td>
<td>-7.24</td>
<td>-6.69</td>
</tr>
<tr>
<td>Upright</td>
<td>-0.88</td>
<td>-0.81</td>
<td>-0.85</td>
</tr>
<tr>
<td>15° Left</td>
<td>3.44</td>
<td>3.08</td>
<td>4.11</td>
</tr>
<tr>
<td>30° Left</td>
<td>5.42</td>
<td>5.30</td>
<td>6.24</td>
</tr>
<tr>
<td>45° Left</td>
<td>7.44</td>
<td>7.28</td>
<td>8.21</td>
</tr>
<tr>
<td>Upright</td>
<td>1.36</td>
<td>1.68</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Mean values of cycloposition (RE/LE), cycloversional offset from reference position (RE + LE/2) and gain of cycloversional compensation of head tilt for each head position during three different test conditions (all data in degrees, clockwise rotations are positive, counterclockwise are negative). Gain is expressed as percentages.

Return of Cycloposition

Another interesting finding in most of the recordings was that cycloversional reorientation after change of head position...
from 45° tilt to upright did not lead to the initial offset cycloposition (Table 1, Fig. 4). Compared with the first reorientation (from right head tilt of 45° to upright head position), the insufficiency was more pronounced after the second reorientation (from left head tilt of 45° to upright head position). Cycloductional reorientation was more precise when the observer was viewing binocularly and with good spatial orientation (test 2) than without spatial orientation (test 1).

**DISCUSSION**

The purpose of our study was to investigate ocular counterroll induced by the BHTT, using a new noninvasive and easily applicable eye movement recording and analysis method, the infrared 3D-VOG technique. The intent was to consider longer fixational periods of several seconds. Short-term cyclopositional instability was not evaluated, because it has been shown usually not to exceed 0.2° and seems to average over time (cf. Table 1 and Fig. 1 in Ref. 8).

In accordance with a number of previous reports, our study, ocular counterroll in response to lateral head tilt was a consistent finding in healthy subjects without disturbances of the ocular motor or the central nervous systems. In light of these studies, we believe that the observations of Jampel and Levine that no real ocular torsion occurs on lateral head tilt must have been based on misinterpreted recording data and cannot be supported any longer.

The procedure that we call stepwise tilting of the head is referred to in the literature as static head tilt, as opposed to dynamic head tilt (i.e., when the head is kept in a continuous sinusoidal lateral tilt movement). The former has been demonstrated to induce less compensatory counterroll than the latter. Collewijn et al. reported a 10% compensation for head inclination when the head was tilted to a steady position of 20°. The compensation increased to between 40% and 70% during voluntary sinusoidal head roll, which was confirmed by the findings of Morrow and Sharpe, who investigated active and passive dynamic head tilt. Because we focused on the phenomena induced by the BHTT that correspond to a static head tilt, we have not reported on dynamic head tilt, except for the dynamic changes during the actual tilting of the head.

**Cycloduction and Gain**

Our study revealed that compensatory cycloduction to head tilt can be of a larger amplitude than previously assumed. The maximum gain of counterroll observed in our study was 27% at a tilt of 15°. This observation is in accordance with data in Averbuch-Heller et al. and Kingma et al., who found a maximum gain of 24% and 22%, respectively, and with Lichtenberg et al. who found an average gain of 19% at 30° tilt. However, these findings amount to more than double those reported by Collewijn et al. and by Diamond and Markham. Whereas Kingma et al. used a video technique similar to that performed in our study, Collewijn et al. obtained their results by means of the magnetic search coil. As has been pointed out in the literature, a possible limitation of the search coil technique is undetected coil slippage leading to underestimation of real torsion that might explain the finding of a lower gain.

In accordance with the observations of other investigators, we found a decrease of gain with increasing amount of head tilt. Whereas maximum gain was 27% at a tilt of 15°, it decreased to 20% at 30° tilt, and to 15% at 45° tilt. In our study, maximum absolute counterroll was 9.3° at 45° head tilt. At 160° whole-body roll in the study of Kingma et al., maximum absolute counterroll was not more than 12°. These findings suggest a kind of saturation of compensatory counterroll. Yet, the question remains open of whether the saturation is based on a mechanically limited torsional capacity in a normally balanced innervation pattern of the extraocular muscles, or whether the saturation originates in a limited response of the otolith reflex.

**Transient Change in Cycloduction**

A consistent finding in all subjects was a saccadelike rapid (peak velocity up to 80 deg/sec) torsional movement in the same direction as the head tilt at the initiation of the head movement. This movement was in the opposite direction of the expected ocular counterroll. It occurred rapidly during the change of the head position and before the actual onset of counterroll. It was immediately followed by a slower return saccade, which was superimposed by a few torsional nystagmus-like beats, with the fast phase in the direction of the initial torsional saccade, which was superimposed by a few torsional nystagmus-like beats, with the fast phase in the direction of the initial torsional movement. This movement was in the opposite direction of the expected ocular counterroll. It occurred rapidly during the change of the head position and before the actual onset of counterroll. It was immediately followed by a slower return saccade, which was superimposed by a few torsional nystagmus-like beats, with the fast phase in the direction of the initial rapid part of the movement. These phenomena were followed by the actual compensatory counterroll. The amplitude of the torsional saccade (ranging from 3° to 10°) usually exceeded the amplitude of the following counterroll. A similar but less consistent phenomenon has been described by Collewijn et al. and found to be related to the velocity of the head movement.

**FIGURE 4.** Mean compensatory cyclorotation in nine head-tilt positions of five normal individuals after head tilt.

**FIGURE 5.** Mean gain of compensatory counterroll of five normal individuals after head tilt.
Whereas no rapid eye movements were detected at slow head tilt, the investigators found several instances of conjugate spontaneous forward cyclorotatory saccades during faster head tilt that sometimes preceded the compensatory cycloduction. This type of torsional saccades induced by head movements has been previously described as a rotatory nystagmus of the dynamic vestibular reflex, after stimulation of the semicircular canals.24,25

**Ocular Counterroll Related to Visual Orientation**

Concerning the question of whether cycloductional response to head tilt is influenced by visual orientation and binocular input, the low sample size of the present study has to be taken into account. However, looking at Figures 4 and 5 and at the data in the tables, we interpret the differences between binocular (test 2) versus monocular (test 3) viewing and fixation with (test 2) versus fixation without (test 1) visual spatial orientation, respectively, as being small and of minor clinical significance. This observation suggests that the compensational response is primarily controlled by the vestibular otolith and that visual stimulation contributes little to this phenomenon. The possible influence on ocular counterroll has been mentioned by Collieijn et al.13 and further elaborated by Curthoys.26 There are indications that visual requirements determine the performance of the vestibulo-ocular reflex arising from both the canals and the otoliths.27

In conclusion, our study demonstrated a consistent considerable compensatory ocular counterroll in response to static lateral tilting of the head in healthy individuals. Because the infrared 3D-VOG technique was reliable in assessing ocular cycloduction and comfortable for the individual examined, we consider this noninvasive technique a promising tool for adding further information to routine clinical investigations in search of disturbances of the oblique eye muscles.

**References**


