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Ocular Torsion Before and After 1 Hour Centrifugation

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ABSTRACT: To assess a possible otolith contribution to effects observed following prolonged exposure to hypergravity, we used video oculography to measure ocular torsion during static and dynamic conditions of lateral body tilt (roll) before and after 1 h of centrifugation with a G_x-load of 3 G. Static tilt (from 0 to 57° to either side) showed a 10% decrease in otolith-induced ocular torsion after centrifugation. This implies a reduced gain of the otolith function. The dynamic condition consisted of sinusoidal body roll (frequency 0.25 Hz, amplitude 45°) about an earth horizontal and about an earth vertical axis (respectively, "with" and "without" otolith stimulation). Before centrifugation the gain of the slow component velocity (SCV) was significantly lower "with" otolith stimulation than "without" otolith stimulation. Apparently, the contribution of the otoliths counteracts the ocular torsion response generated by the semicircular canals. Therefore, the observed increase in SCV gain in the condition "with" otolith stimulation after centrifugation, seems in correspondence with the decreased otolith gain in the static condition.

KEY WORDS: Hypergravity, Otoliths, Adaptation, Vestibulo-ocular reflex.

INTRODUCTION

Previous experiments have shown that a prolonged exposure to hypergravity (2–3 G) by means of a human centrifuge, can provoke postural instability and motion sickness for several hours afterwards [1,3,4]. The centrifuge run itself was not experienced as very stressful by the subjects, but the effects arose after reentry to normogravity (1 G). The strongest effects were seen during head movements which changed the orientation of the head with respect to the gravitational vertical. Medical monitoring showed that a cardiovascular cause was highly unlikely [5], which supported the idea of vestibular adaptation to the altered G-environment. Because of the sustained linear acceleration, especially the otolith function is considered responsible in this respect.

The aim of the present study was to identify otolith adaptation by measuring the effects of such a hyper G-load on the ocular torsion (OT) response to lateral body tilt (''roll'' about the subject's x-axis). The OT response to static tilt is attributed to the otoliths [7,11]. Hence, it would suffice to examine OT in static situations only. However, as mentioned above, the observed effects of centrifugation were most marked in a dynamic situation, namely, during head movements. This points to a disturbed interaction between the otoliths and the semicircular canals. Therefore, we extended the OT measurements to dynamic roll stimuli, so that the semicircular canals also contribute to the OT response. To discriminate between the behavior of the otoliths and the semicircular canals, the dynamic roll was performed about an earth horizontal and about an earth vertical axis (respectively, ''with'' and ''without'' otolith stimulation). In this way, activation of the semicircular canals is the same during both conditions, while the otoliths are stimulated only during roll about the earth horizontal axis.

The results indicate that the gain of the otoliths is reduced as a consequence of centrifugation.

METHOD

Centrifuge

Eleven healthy subjects, six men and five women, were exposed to 1-h centrifugation. The centrifuge was located at the neighbouring Netherlands Aerospace Medical Center. Its free swinging gondola, mounted to a 4 m long arm, allowed for a G_x-load of 3 G, because the subjects were in supine position. The centrifuge was accelerated and decelerated with 0.1 G/s. For technical procedures and medical precautions during the experiment, reference is made to [3].

OT Measurements

The OT response was measured during both static and dynamic body tilt about the anteroposterior x-axis (''roll''). The subjects were seated in the TNO-tilt chair, the rotation axis being centered between both eyes. The subject's head was supported by a head rest, and the body was firmly strapped to the chair. OT measurements were performed once before (pretest), and once after (posttest) the centrifuge run. The posttest generally took place 20 min after the centrifuge run.

In the static tilt condition, subjects were seated upright and the rotation axis was oriented earth horizontally. OT was recorded at tilt angles of 0, 10, 20, 30, 42, and 57° to the left and to the right.

The dynamic roll stimulus consisted of 10 cycles of sinusoidal oscillation with a frequency of 0.25 Hz and an amplitude of 45°. This stimulus was applied in an upright body position first (roll axis parallel to the earth horizontal), and, after 5 min rest, in supine body position (roll axis parallel to the earth vertical). When the axis of roll was earth horizontal, subjects oscillated in roll ± 45°, where 0° was the position in which the z-axis came into alignment with gravity.

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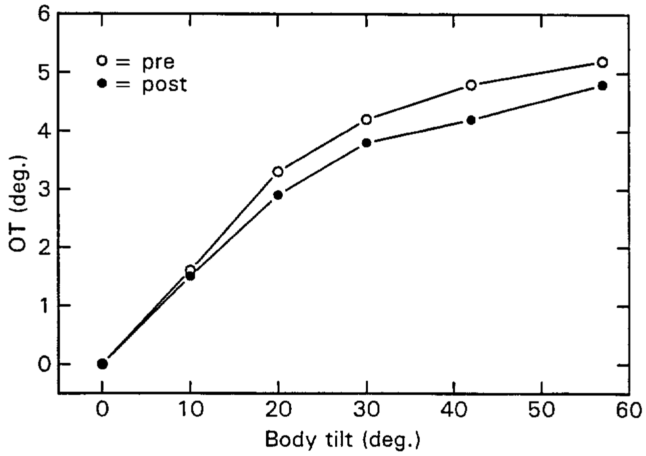

FIG. 1. Average OT response to static lateral body tilt, before and after centrifugation. The response was decreased by 10% due to centrifugation.

Video-oculography

Eye movements of both eyes were recorded simultaneously on video tape by means of small CCD-video cameras mounted to a head set and placed 2 cm in front of the eyes, the optical axes aligned with the visual axes. Except for a point source of white light, fixed to each camera for illumination of the eyes, the measurements were performed in darkness. Video recordings were analyzed afterwards. For each angle of static tilt, an image was digitized, and OT was quantified by means of a semiautomatic method described by Bos and De Graaf [6]. The OT response to dynamic roll was quantified automatically with a sample frequency of 50 Hz, using an automatic system that we developed for this purpose [10]. Both methods achieve a practical accuracy better than 0.25°.

For the analysis of the OT response to dynamic roll, the first three periods were disregarded to allow for build up of the response. From the remaining seven periods, two parameters were calculated, using an interactive computer program. First, the torsional VOR gain was calculated by dividing the amplitude of the slow component velocity (SCV) by the amplitude of the stimulus velocity, (V_{max} = 70°/s). The SCV amplitude was obtained by means of a sinusoidal fit, which was applied to the OT signal after digital differentiation and saccade removal. Second, the average amplitude of the original OT signal was calculated to quantify the total amount of torsional displacement (''beating field''), analogous to the Schlagfeldverlagerung or gaze shift measured in optokinetic and cervico-vestibular studies [4,8]. Whereas the SCV is related to the slow component only, the beating field also concerns the saccades.

RESULTS

Static Tilt (Pre- vs. Postcentrifugation)

Because averaged OT values were the same for both eyes, and no differences were observed in the OT response to either side of tilt, the data were pooled. Figure 1 shows the static OT curve from the pretest and the posttest. In the posttest, OT was 10% smaller than in the pretest (Student's *t*-test: $p < 0.05$).

OT Response to Dynamic Tilt ''With'' and ''Without'' Otolith Stimulation (Pretest)

The difference in OT response to body roll in upright and supine body position is clearly illustrated in Fig. 2 for one subject. In both conditions, the OT recordings show a compensatory eye movement, interrupted by anticompensatory saccades.

For all calculations, data from right and left eye were averaged. The SCV gain was significantly smaller (Student's *t*-test: $p < 0.05$) in the condition ''with'' otolith stimulation (mean gain = 0.31, corresponding to a mean peak eye velocity of about 22°/s) than in the condition ''without'' otolith stimulation (mean gain = 0.36). The average amplitude of the beating field, on the contrary, was significantly larger (Student's *t*-test: $p < 0.01$) ''with'' otoliths (8.0°) than ''without'' otoliths (3.4°), apparently due to differences in saccadic activity.

In both conditions the average phase lead of the OT response amounts to 40° with respect to the inverted stimulus (to account for the fact that an optimal compensatory response would be shifted 180°).

Dynamic Tilt (Pre- vs. Postcentrifugation)

In the ''with'' otoliths condition, the SCV gain increased in 10 subjects, and did not change in one subject. The mean gain value increased from 0.31 (± 0.049) in the pretest to 0.35 (± 0.057) in the posttest (Student's *t*-test: $p < 0.01$). In the ''without'' otoliths condition, however, the mean SCV gain and standard deviation remained unchanged (0.36 ± 0.044 in the pretest,

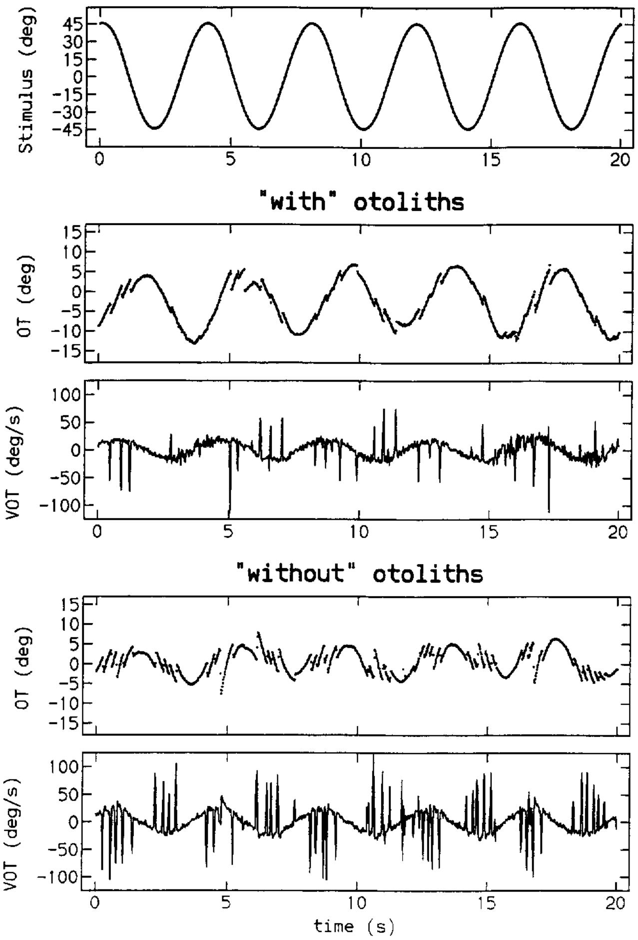

FIG. 2. Pretest OT response (eye position and velocity) of one subject during sinusoidal body roll about an earth horizontal axis (''with'' otolith stimulation) and about an earth vertical axis (''without'' otolith stimulation). The upper trace represents the stimulus.

and 0.36 ± 0.055 in the posttest). The individual gain values, however, showed a divergent behavior: the gain increased in six subjects, decreased in four others, and remained unchanged in one subject. As a consequence, the apparent difference in gain change between both conditions ("with" and "without" otoliths) was not statistically significant [ANOVA: $F(10) = 2.0, p < 0.18$]. Averaged over both conditions, the gain increased significantly from 0.34 in the pretest to 0.35 in the posttest [ANOVA: $F(10) = 4.8, p < 0.05$]. The mean SCV values and the standard deviations for all four conditions are shown in Fig. 3.

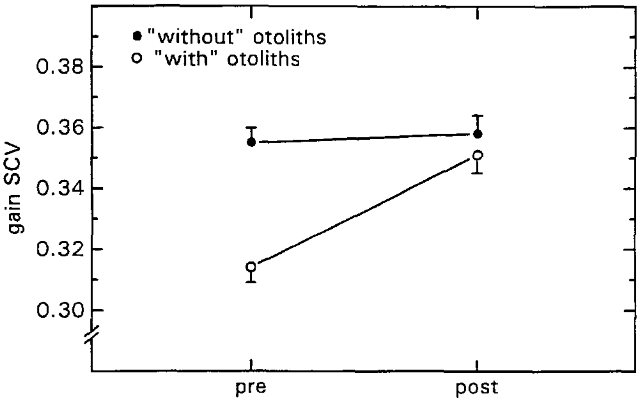

FIG. 3. The mean values of the gain of the slow component velocity in the "with" and "without" otoliths conditions, before and after centrifugation. The bars indicate the standard deviation. Although the increase in the "with" otolith condition is statistical significant between the pre and posttest, this behavior does not differ significantly from the "without" otoliths condition.

DISCUSSION

The results from the static test suggest that the otolith function adapted due to 1-h $+3G_x$-load, as was indicated by a 10% reduction of the OT gain.

With respect to the dynamic conditions, it is not remarkable that the OT response to sinusoidal body roll depends upon orientation relative to gravity. It is remarkable however, that the combination of canal and otolith stimulation yields a response that is less than the response generated by the canals alone. Although the amplitude of the beating field is higher "with" otolith stimulation, the compensatory peak eye velocity is lower than "without" otolith stimulation. Apparently, at the frequency of 0.25 Hz, the otolith function counteracts the torsional VOR induced by the semicircular canals. This finding is not reported earlier in the literature: the canal-induced torsional VOR was either found to be independent of otolith stimulation [13], or it was found to be increased by otolith stimulation [2]. In the present study, the opposed contributions of the otoliths and the canals can possibly be explained by a phase difference in their response. This idea is supported by results from OT measurements during lateral sinusoidal oscillation on a linear track, which we performed recently [9]: at a stimulus frequency of 0.22 Hz, the otolith-induced OT response showed a phase difference of 120° with the canal-induced OT response in the "without" condition from the present study. Although summation of both responses may be a too simple approach [14], this phase difference does result in a total response that is smaller than the response induced by the canals alone.

The observed otolith-canal interaction is in agreement with the increase of the VOR gain in the "with" otoliths condition after centrifugation. As a result of the reduced otolith gain, observed in the static tilt condition, the counteracting effect on the VOR would be less, thereby increasing its gain. This reasoning is based on the assumption that the canal function is unaffected by the centrifuge run. The "without" otoliths condition served as a control condition in that respect. Although the OT response on average did not change in this condition, the individual responses behaved inconsistently. Consequently, no decisive statistical evidence was found to attribute the increased VOR gain exclusively to a changed otolith gain.

ACKNOWLEDGEMENTS

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COMMENTARIES

Congratulations to you and your colleagues for an interesting experiment, and to you for developing the pattern-recognition program that measures ocular torsion. I hope that you and others in this meeting who have developed similar programs will get together and tell us how best to do it.

Your results raise questions about the nature of the adaptation that occurs during hyper-G exposure and perhaps more questions about responses to canal-otolith interactions, as they may be influenced by the distinctive functions of the canal and otolith systems. I would be interested in your response to the following points:

1. Have you conducted experiments in which the zero position is displaced from gravity during the dynamic otolith+canal stimulation? In other words, instead of oscillating ±45° relative to gravity, displace the zero position 10° or 20° relative gravity and oscillate sinusoidally about that point. This would place the canal- and otolith-mediated responses in a different relationship.
2. You found lower OT-SCV gain for the canal+otolith stimulus than for the canal stimulus, and you interpreted this result in terms of different phase angles of canal- and otolith-mediated responses. A related but different interpretation is that otolith-mediated ocular torsion, whatever its function, has a limited functional range, and the absence of otolith-mediated OT beyond 5–10° provides functionally useful retinal slip tilt information. According to your static tilt data, the maximum OT expected for a 45° head tilt is 5°. Assuming that the OT responses to the sinusoidal stimulus is truly sinusoidal, the maximum otolith-mediated OT velocity, calculated from $[(5^\circ \times 2\,\mathrm{pi})/5\mathrm{s}]$, is less than 8°/s. At the same time, the canals would be responding to a peak velocity of roughly 70°/s, and otolith-mediated OT might slightly increase the gain of the canal+otolith response, but, is it functionally advantageous for the otolith system to increase the gain when the eye is directed to a target along the x-axis? Perhaps it is functionally effective to have peripheral retinal image velocity for head rolls that exceed 5 or 10°.
   Have you evaluated OT during sinusoidal oscillation within the ± 10° range?
3. In your dynamic without-otolith stimulus, the subject's gaze was directed to a point along the x-axis. In this situation, the eye rotates around the x-axis (x-axis of the head and x-axis of the eye). If the point were the center of a head-fixed display, visual acuity for the center of the display would be degrated very little, but peripheral images would become more fuzzy and appear to move. If the display were earth-fixed, clarity of the center of the display would be improved only a little but clarity of the peripheral display would be improved by canal+otolith mediated OT velocity with a gain of 1. Whether or not a gain of 1 is functionally advantageous may depend upon the direction of gaze and the goal-directed behavior of the individual. Now consider a subject who experiences exactly the same vestibular stimulus while gazing to a point 45° laterally. The eye will still rotate around the x-axis of the head but it will rotate about an eye axis midway between the x and y axes of the eye. In this eye orientation, the same eye velocity will yield much greater velocity and displacement of retinal image relative to the fovea. With this direction of gaze relative to the path of head movement a gain of canal+otolith mediated eye velocity will be desirable for central and peripheral vision and also to achieve the goal of the individual. In your canal+otolith dynamic stimulus the gain of the eye movement response, its augmentation or reduction, by a dynamic otolith stimulus may depend upon the direction of gaze. Have you evaluated the influence of gaze direction on the eye movement response? This could be evaluated by comparing visual acuity for lateral targets with and without the presence of the dynamic otolith stimulus.
4. What was the orientation of the subject's head relative to the body during the 3 G exposure and what was the orientation of the 3 G vector relative to the otolith membranes of the utricle and saccule? Was the head elevated relative to the body? Have you examined the influence on postexposure effects of head position relative to the body during the 3 G exposure?
5. You refer to the change in the OT response following the sustained 3 Gx exposure as being indicative of otolith adaptation. Frequently, adaptation refers to a change in response that in some way improves the state of the adapted individual. For example, dark adaptation improves night vision. Light adaptation improves vision upon returning to daylight. The adaptive plasticity of the Gonshor/Jones optical distortion paradigm alters the VOR in ways that improve the individual's ability to operate in the new environment. In what way does the reduced otolith response following the 3 G exposure improve the state of the individual who is lying supine in the 3 G environment? Please indicate the meaning of adaptation as you are using it.

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Point 1

Displacement of the zero position of oscillation is a very interesting option. For the present study, oscillation about one zero position during the conditions "with" and "without" otoliths was expected to be sufficient to identify otolith adaptation. The differences in the OT response in both conditions argue, however, in favour of more detailed investigation of the canal-otolith interaction itself. In this respect, we like to mention that we are momentarily analysing data from an experiment, in which we measured OT at various frequencies and amplitudes of sinusoidal roll in the upright and the supine body position. Up to now, we did not vary the zero position of oscillation (yet).

Point 2

Although we think that an amplitude of 45° is not beyond the ecological range, you could be right that smaller tilt angles will be better compensated for by the OT response. But should this not be reflected in the static measurements as well, where OT already falls behind at small tilt angles?

Indeed, it is questionable whether the otolith system is needed to improve the OT gain to dynamic roll tilt: although low, the gain of the canal-mediated OT might be satisfactory already. Interestingly, the otolith system affected the beating field more dramatically than the SCV gain: otolith contribution increased the average beating field from 3.4° to 8.0° (more than 100%), whereas the SCV gain decreased from 0.36 to 0.31 (about 15%). Possibly, the goal of the otolith system is to define an offset position for the eyes, rather than to compensate for head velocity. This makes your suggestion to displace the zero position of oscillation (point 1) extra relevant.

Point 3

An interesting thought. We have no data on this, because it is technically impossible for us at present. In the view of the "low" gain of the OT response to roll tilt, one may doubt whether ocular torsion serves visual acuity at all. Presumably, its gain is adequate enough for spatio-temporal orientation.

Point 4

In a series of experiments we examined the relation between Space Adaptation Syndrome (SAS) and Sickness Induced by long duration Centrifugation (SIC) [1]. The subjects were centrifugated in supine position, but the head was positioned such that stimulation took place either along the x-, the y-, or the z-axis of the head. OT was registered during active head movements before and after the run, but unfortunately the video-oculography technique at that time did not allow for adequate analysis. A comparison showed that x-, y-, and z-axis stimulation did not differ in terms of SIC, which suggests a central mechanism. This idea is supported by the present study, where changes in OT by stimulation about the x-axis (roll) were found, whereas the centrifuge run increased the G-force along the x-axis.

Point 5

During the centrifuge run, subjects were in supine position and did not make head movements. This may seem a passive situation, but for the otolith system this does mean constant stimulation with 3 G. Normally, the otolith system operates in an invariant force field of 1 G.

The basic activity ("set point") and sensitivity of the system is optimally adjusted, so that small stimuli can be detected against this constant background stimulation. Increasing the background level from 1 G to 3 G will shift the set point away from its ideal position. Adaptation will restore the operational range of the otolith system within its normal limits. After prolonged exposure to 3 G, the opposite process (readaptation to 1 G) will be required. After the run, head movements elicited illusory motion of the visual world and provoked SIC in 50% of the subjects, indicating that otolith information no longer matched the concurrent information from other sensory systems.

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