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Perception of tilt and ocular torsion of vestibular patients during eccentric rotation

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ABSTRACT

Four patients following unilateral vestibular loss and four patients complaining of otolith-dependent vertigo were tested during eccentric yaw rotation generating $1 \times g$ centripetal acceleration directed along the interaural axis. Perception of body tilt in roll and in pitch was recorded in darkness using a somatosensory plate that the subjects maintained parallel to the perceived horizon. Ocular torsion was recorded by a video camera. Unilateral vestibular-defective patients underestimated the magnitude of the roll tilt and had a smaller torsion when the centrifugal force was towards the operated ear compared to the intact ear and healthy subjects. Patients with otolithic-dependent vertigo overestimated the magnitude of roll tilt in both directions of eccentric rotation relative to healthy subjects, and their ocular torsion was smaller than in healthy subjects. Eccentric rotation is a promising tool for the evaluation of vestibular dysfunction in patients. Eye torsion and perception of tilt during this stimulation are objective and subjective measurements, which could be used to determine alterations in spatial processing in the CNS.

The otolith organs detect linear acceleration of the head and tilt relative to gravity. This information is used by the CNS for maintaining our spatial orientation in relation to the surrounding environment. In a recent study [10] we observed that, unlike unilateral vestibular-defective patients, patients who presented signs of otolithic disorders show alterations in their mental representation of space. The objective of this study was to contrast the oculomotor and perceptual responses to eccentric rotation in the same subjects to assess if a distinction between vestibular patients was also present during this stimulation. Indeed, eccentric rotation by means of a short-radius centrifuge has been advocated as a promising tool for investigating vestibular pathophysiology [6]. The effects of eccentric rotation on patients with unilateral vestibular ablation have been previously reported [14,15]. Very few studies have investigated the effects of eccentric rotation on patients with isolated, peripheral otolith dysfunction [7,19,30]. Specifically, the question addressed in our study was of whether patients with central signs of spatial processing disorders exhibit the same magnitude of eye torsion and perceived roll tilt during centrifugation than unilateral vestibular patients and healthy subjects.

A subject seated upright during eccentric yaw rotation at constant velocity is exposed to a tilted linear acceleration vector that is the sum of centrifugal force along the interaural axis and the force of gravity (Fig. 1). The centrifugal force is a shear force acting on the utricles, which generates a torsion of the eyes around the line of sight, known as counter-rotation and a perception of body tilt in roll, known as the somatogravic illusion [8]. Although this stimulus will cause both somatosensory and vestibular stimulation, the effect clearly depends mainly on vestibular function since early investigations demonstrated that individuals with bilateral vestibular deficits do not experience roll tilt sensation to nearly the same extent as normal subjects [5]. During eccentric rotation, normal healthy subjects show symmetrical eye torsion and perceptual responses for symmetrical but oppositely directed linear acceleration stimuli along their interaural axis. The magnitude of roll tilt perception in naïve subjects is slightly larger than the angle of the resultant linear acceleration vector [8,9,24].

Eight vestibular patients (5 females and 3 males) between the ages of 38 and 56 (mean 44.7) participated in this experiment. Their responses were compared to those of 11 healthy subjects (6 females and 5 males) between the ages of 28 and 43 (mean 33.2 years) who had been previously tested in the same conditions [9]. The vestibular patients were selected between two groups of patients who participated in another study [10], i.e., 29 patients with rotatory vertigo and 27 patients with otolithic vertigo. The eight patients selected for the present study were typical from each group.

Four patients had undergone complete unilateral vestibular ablation due to surgical removal of vestibular neuroma (two left and two right) at 5, 10, 13, and 32 months prior to testing. During stimulation of the intact ear the caloric responses were within the

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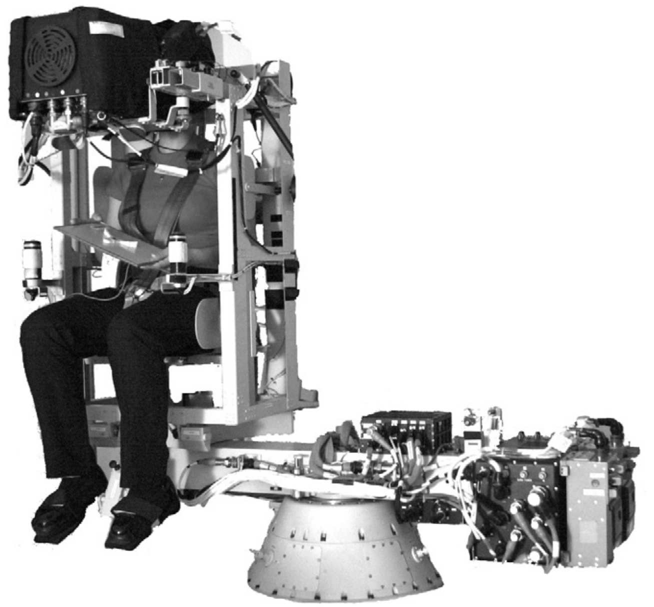

Fig. 1. Photograph of the ESA human short-radius centrifuge used in this study. The subjects were sitting upright at a distance of 0.5 m from the axis or rotation. They were facing-motion or back-to-motion, so that the centrifugal force of $1 \times g$ generated by eccentric rotation was aligned with their interaural axis. The resultant of the centrifugal force and the force of gravity was tilted 45° relative to Earth vertical, and consequently, the subjects in darkness had the illusion of their body being not vertical but tilted outwards during centrifugation, e.g., to the right for the orientation shown in this figure. They indicated this magnitude of perceived tilt by orienting a plate that they were holding in their hand along the (perceived) horizontal plane. Eye movements were also recorded by infrared video camera.

normal range. During rotational tests using velocity steps (100 °/s) and sinusoidal (0.05 Hz and 0.2 Hz, 60 °/s) stimulation, there was only a slight (<10%) decreased nystagmus response during rotation towards the operated ear compared to the intact ear, thus indicating vestibular compensation.

Four other patients experienced typical otolithic syndrome signs, including vertical falling, rising, or floating sensation; erroneous sensation of linear motion during transportation; and perceived tilt or distortion of the body or the environment [2]. None of these patients had identified peripheral or central lesion. The caloric and rotational responses, as well as the vestibular (saccule) evoked myogenic potentials of these patients with otolith-dependent vertigo showed no evidence of clinical abnormalities. The subjective visual vertical estimation when stationary in darkness (a screening test of utricular function) showed a larger variability in these patients compared to the vestibular-defective patients and the healthy subjects, but no systematic deviation to one side [9,10]. The results of these tests suggested that spatial processing in the CNS was disturbed in these patients.

This study used the human short-arm centrifuge developed by the European Space Agency [24] (Fig. 1). All procedures were in accordance with the Declaration of Helsinki and were approved by the local Institutional Review Board. Subjects were seated upright with the body vertical axis parallel to the axis of rotation at a distance of 0.5 m from the center. They were facing the tangent and were oriented either left-ear-out (LEO) or right-ear-out (REO) (Fig. 1). A restraint system consisting of a 5-point harness, thigh, shoulder, and neck pads held the body firmly in place. The subject's head was restrained to the chair structure and to the visual display by a custom-made facemask such that Reid's baseline was horizontal and orthogonal to the axis of rotation [24].

Black dots were presented on a computer visual display mounted in a box directly in front of the subject's face for calibration purposes prior to testing. Left eye movements were recorded in infrared light by a miniature NTSC video camera mounted on the visual display unit via an infrared beam-splitter that was transparent to light in the visible range, allowing the subject a clear view of the visual display.

The subjects held in their hands a somatosensory plate (SP) made of stiff cardboard measuring 21 cm × 29 cm (Fig. 1). Attached to the SP was a commercially available three-dimensional mouse (Logitech Inc., Fremont, CA, USA), which received ultrasound signals emitted by a transmitter mounted on the centrifuge. These signals were relayed to a control unit that converted the delays into successive (frequency 9 Hz) three-dimensional position (X, Y, Z) and rotation (pitch, yaw, roll) of the SP. These coordinates were stored in the command and control computer along with the centrifuge parameters. The resolution in the pitch, yaw, and roll rotations was 0.1° [9].

In each run, subjects were initially accelerated at 26°/s^2 to a constant angular velocity of 254°/s which generated a tangential acceleration of $0.023 \times g$ along their naso-occipital axis for 9.8 s and, when constant velocity was achieved, a centripetal acceleration along their interaural axis of $1.0 \times g$. After 60 s at constant velocity, subjects were decelerated at 26°/s^2 to rest. The subjects were in complete darkness during the entire run and were instructed to maintain the SP aligned with their subjective estimation of horizontal at all times, without touching the chair structure. The subjects' instruction was "imagine that the plate you are holding is supporting several glasses filled with water: you must maintain it perfectly horizontal so that the liquid does not spill". A trial consisted of clockwise LEO (facing-motion) rotation, counterclockwise LEO (back-to-motion), counterclockwise REO (facing-motion), and clockwise REO (back-to-motion), in random order. The subjects were generally confused during their first run and therefore this run was repeated twice, with only the latter being included in the analysis.

Before rotation, while sitting in the centrifuge's seat immobile in darkness, the subjects were presented with the SP along the true horizontal and asked to position the SP to various angles of tilt in pitch and in roll by increments of 15°. A linear curve fit forced through zero was calculated for each subject during this calibration for both the roll and pitch rotations. The formula of these curve fits were used to compute the ratio between the required and the achieved angle for both roll and pitch, and these ratios were then applied to the SP settings during eccentric rotation [9].

Eye video images were processed field by field, providing a sampling rate of 60 Hz. The coordinates of the pupil center in the image field were calculated using a partial ellipse fit. Torsion eye position was obtained using polar cross-correlation of the grey-level intensity information of the iris sampled from a circular annulus centered on the pupil [24]. As demonstrated in previous studies it is important to differentiate the ocular torsion associated with the otolithic stimulation by the centripetal acceleration from that due to the activity of the semicircular canals during spin-up and spin-down [27]. During facing-motion eccentric rotation, the ocular torsion in response to the centripetal acceleration is in a direction opposite to that produced by the angular acceleration during spin-up. On the contrary, during back-to-motion eccentric rotation, centripetal and angular accelerations produce co-directional ocular torsion. Consequently, averaging the ocular torsion components for both the facing-motion and back-to-motion stimuli reveals the changes in ocular torsion generated by the sole centripetal acceleration [9].

During eccentric rotation all the subjects with unilateral vestibular loss experienced the somatosensory illusion and reported a roll tilt of their body towards the left in LEO and towards the right in REO, and they tilted the SP in the opposite direction. Their eyes also counter-rolled to the right in LEO and to the left in REO. Their sense of tilt in both the pitch and roll planes and