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RESEARCH ARTICLE

Otolith-Ocular Reflex

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Abstract

Purpose: The otolith organs are the utricle and saccule, and their function is to sense gravity and linear acceleration. We performed several physical experiments to determine whether nystagmus occurs when stimulating the otolith organs.

Methods: Subjects were five healthy humans with no ear pathologies. Experiment 1 (sway): Subjects stood with their feet shoulder-width apart and, with their neck in a fixed position, were asked to alternate between lifting their heels on the left and right, thereby translating their head laterally for three cycles. Experiment 2 (squat): Subjects were asked to stand with feet shoulder-width apart and perform three vertical squats. Eye movements were recorded and converted to digital data.

Results: None of the subjects exhibited nystagmus in both experiments.

Conclusions: Otolith organs do not cause nystagmus. Therefore, eye movement's analysis cannot evaluate the function of otolith organs, and the ocular counter-roll is a semicircular canal ocular reflex.

Keywords

Otolith organ, Utricle, Saccule, Linear acceleration, Video-oculography, Inertial force

Introduction

The otolith organs are the utricle and saccule, and their function is to sense gravity and linear acceleration. Hair cells in the otolith organs are always transmitting crucial information regarding head position to the vestibular nucleus. The mechanism of sensation is the bending of the cilia.

Once the ocular counter-roll was discovered, it was assumed that the otolith organs are involved in eye movements. Curthoys [1] reported that upward eye movements were evoked by stimulation to the unilateral macula of the utricle, while Goto, et al. [2] showed that horizontal eye movements were evoked by the selective stimulation of the utricular nerve in cats. Additionally, Furman, et al. [3] reported that off-vertical axis rotation has the potential of becoming a useful method for clinical assessing both the otolith-ocular reflex and semicircular canal otolith interaction.

However, these findings should be treated with caution because of the Epley maneuver [4]. Pathophysiology of benign paroxysmal positional vertigo is pathological debris in the semicircular canal. The principle of the Epley maneuver is moving debris from a long arm to the utricle. We have noticed that no one showed nystagmus in the sitting position after the treatment. Just after the Epley maneuver, pathological debris stimulates the macula of the utricle. Nevertheless, no patient complained of vertigo and no patient revealed nystagmus.

We therefore performed several physical experiments to determine whether nystagmus occurs when stimulating the otolith organs, and to confirm the direction of the inertial force.

Materials and Methods

Subjects of Experiments 1 and 2 were five healthy humans with no ear pathologies.

Experiment 1 (sway)

First, it was confirmed that yaw, pitch, and roll rotations of the head can develop good horizontal, vertical, and torsional nystagmus. Second, subjects stood with their feet shoulder-width apart and, with

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Table 1: Results of experiment 1 and 2.

			Experiment 1	Experiment 2
Subject	Age (years)	Sex	Nystagmus	Nystagmus
1	33	Female	-	-
2	43	Female	-	-
3	53	Female	-	-
4	64	Male	-	-
5	65	Male	-	-

their neck in a fixed position, were asked to alternate between lifting their heels on the left and right, thereby translating their head laterally for three cycles. Frequency was approximately 0.33 Hz, and amplitude was approximately 0.3 m. Eye movements were recorded and converted to digital data.

Experiment 2 (squat)

Subjects were asked to stand with feet shoulder-width apart and perform three vertical squats. Frequency was approximately 0.33 Hz, and amplitude was approximately 0.3 m. Eye movements were recorded and converted to digital data.

Experiment 3

An orange plastic cap was placed on the tip of a spring, before being jerked sideways. The movement was recorded.

Experiment 4

An orange plastic cap was placed on the tip of a spring, before being jerked downward. The movement was recorded.

Eye movement's analysis

Experiments 1 and 2 were performed in the dark with the subjects' eyes open using an infrared charge-coupled device camera. Eye movements were recorded and converted to digital data. Three-dimensional video-oculography was performed using ImageJ version 1.36 software (a public domain, Java-based image-processing program developed at the National Institutes of Health). For analysis of the horizontal and vertical components, the XY centre of the pupil was calculated. For analysis of the torsional component, the whole iris pattern, which was rotated in steps of 0.1°, was overlaid with the same area of the next iris pattern, and the angle at which both iris patterns showed the greatest match was calculated [5].

Results

Table 1 shows the results of Experiments 1 and 2. Movies show the results of all experiments [6].

Experiment 1

None of the subjects exhibited nystagmus. Figure 1 shows the video-oculography of Subject 5.

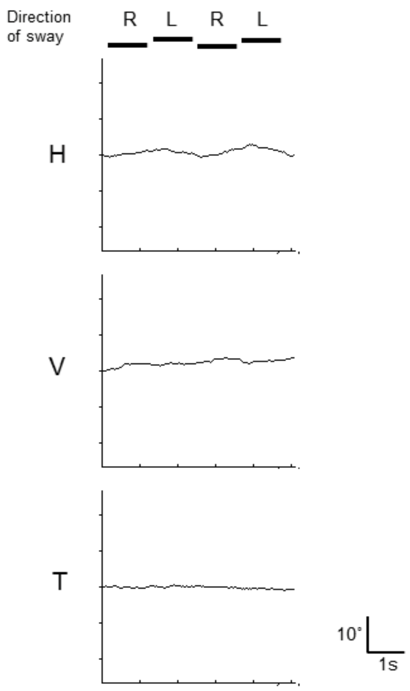

Figure 1: Video-oculography (position trace) of Subject 5. Sway did not produce nystagmus. The upward deflections in horizontal (H), vertical (V), and torsional (T) eye movements are indicated as being toward the right, upward, and right, respectively. R: Right; L: Left.

Experiment 2

None of the subjects exhibited nystagmus. Figure 2 shows the video-oculography of Subject 5.

Experiment 3

At the beginning of the movement, the orange cap moved to the left, in the opposite direction to the acceleration.

Experiment 4

At the beginning of the movement, the orange cap moved upward, in the opposite direction to the acceleration.

Discussion

Our results showed that the otolith organs do not cause nystagmus.

The results of Experiment 3 show that an object receives an inertial force in the opposite direction to the acceleration. This is Newton's first law, which states that anything at rest has the tendency to stay at rest. The resulting inertial force is the product of mass and acceleration.

In Experiment 1 (sway), lateral linear acceleration should have induced inertial forces on the otoconia, stimulating the utricle. The results showed that no nystagmus occurred, confirming that nystagmus does not arise from the utricle.

For convenience, we assumed that one otoconium sits on the top of one hair cell in the utricle (Figure 3). Where the mass of an otoconium is m, the weight of the otoconium is mg. Because the otoconium is present in the endolymph, a buoyancy is generated with a magnitude of ρVg (Archimedes' principle). Therefore, the force F1 that the otoconium presses against the otolithic membrane is mg-ρVg. If an acceleration (magnitude of it is a) is applied to the left, the resulting inertial force F2 is the apparent mass (m-ρV) multiplied by a. This force deforms the otolithic membrane and causes the bending of cilia toward the right. However, no nystagmus was observed, confirming that the utricle does not cause nystagmus.

The results of Experiment 4 show that an inertial force also occurs in the vertical direction, in the opposite direction to the acceleration.

In Experiment 2 (squat), the saccule should be stimulated by the inertial force generated by the vertical linear acceleration. However, the fact that nystagmus does not occur is evidence that nystagmus does not arise from the saccule.

Again, for convenience, we assumed that one otoconium sits on the top of one hair cell (Figure 4). If the mass of the otoconium in the saccule is m, the weight of the otoconium is mg. Because the otoconium is present in the endolymph, a buoyancy is generated, with a magnitude of ρVg. Therefore, the force F3 exerted on the otoconium is mg-ρVg. When a downward acceleration (magnitude of it is a) is applied by squatting, the resulting inertial force F4 is the apparent mass (m-ρV) multiplied by a. This force deforms the otolithic membrane of the

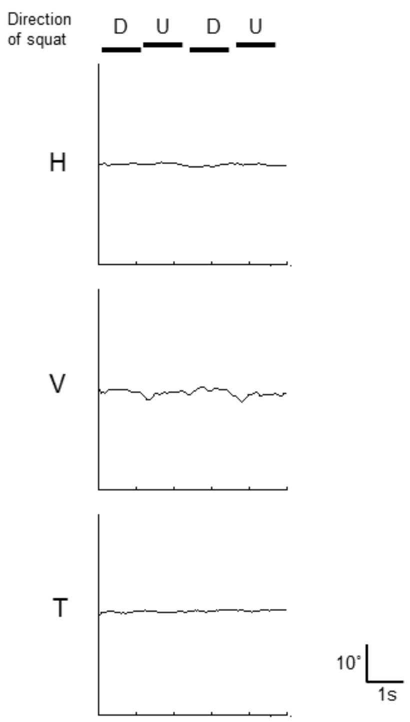

Figure 2: Video-oculography (position trace) of Subject 5. Squat did not produce nystagmus. The upward deflections in horizontal (H), vertical (V), and torsional (T) eye movements are indicated as being toward the right, upward, and right, respectively. D: Downward; U: Upward.

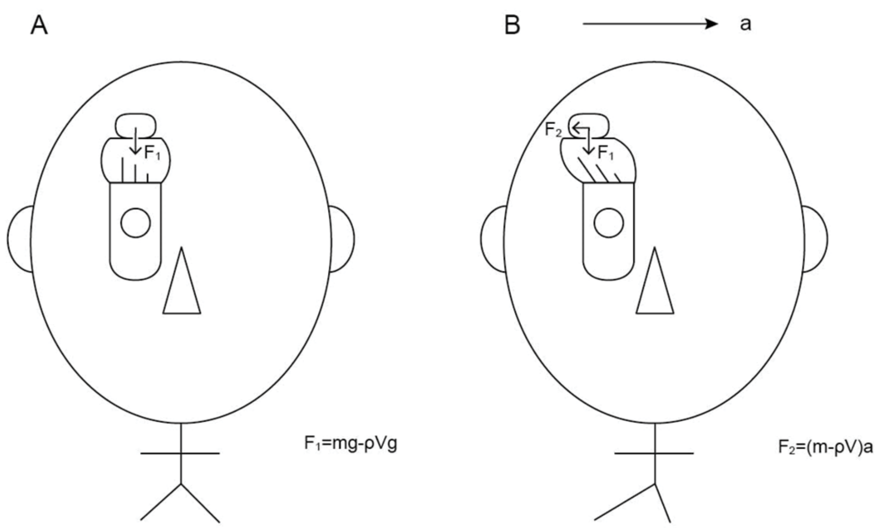

Figure 3: (A): Rest; (B): Sway to the left. Inertial force deforms the otolithic membrane and causes the cilia to bend to the right. However, the eyeball did not move, confirming that the utricle does not produce nystagmus. A: Acceleration of the head; m: Mass of the otoconium; g: Gravitational acceleration; ρ: Density of endolymph; V: Volume of the otoconium.

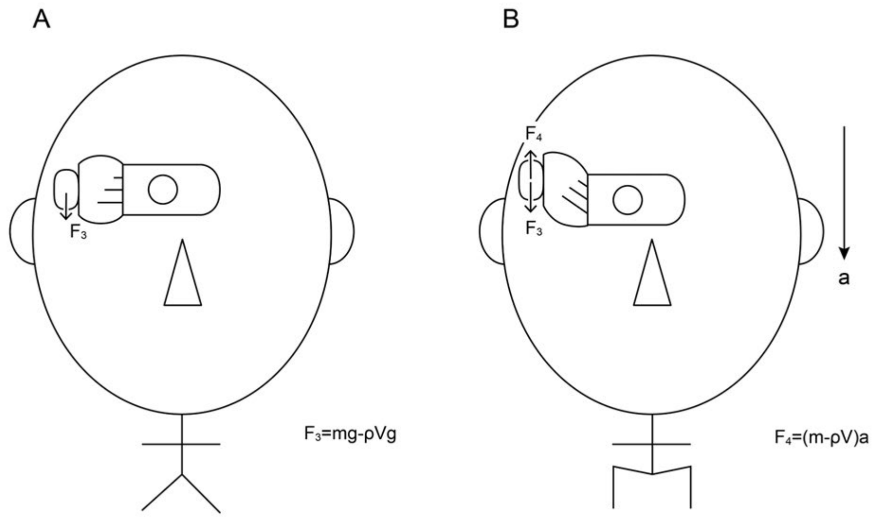

Figure 4: (A): Rest; (B): Squat down. Inertial force deforms the otolithic membrane of the saccule, bending the cilia of the hair cell upward. However, the eyeball did not move, meaning that the saccule does not produce nystagmus. A: Acceleration of the head; M: Mass of the otoconium; g: Gravitational acceleration; ρ: Density of endolymph; V: Volume of the otoconium.

saccule, bending the hair cell cilia upward. However, no nystagmus was produced, confirming that the saccule does not cause nystagmus.

Theoretical physics can explain why nystagmus does not originate from the otolith organs. All animals, including humans, sense gravity through their otolith organs. Specifically, both saccule and utricle are constantly stimulated by gravity. Even in an upright position, action potential occurs in a hair cell, because the weight of otoconia pushes the cilia. Even if the head is stationary, a hair cell is transmitting crucial information regarding head position to the vestibular nucleus. Namely, vestibular nerves are continuously stimulated throughout the lifetime of every animal on Earth. If nystagmus were to be generated by the action potential of hair cells, all animals should be constantly producing nystagmus. However, this is not the case. Therefore, we can conclude that nystagmus is not caused by the otolith organs.

Maximising the angle of flexion of the cilia of the utricle can be easily achieved by lying in a lateral position. In the right lower lateral position, gravity pushes the cilia to the right (Figure 5). If the ocular counter-roll was the utricle ocular reflex, leftward torsional nystagmus should continue with this head position. However, nothing happens, which proves that nystagmus does not originate from the utricle.

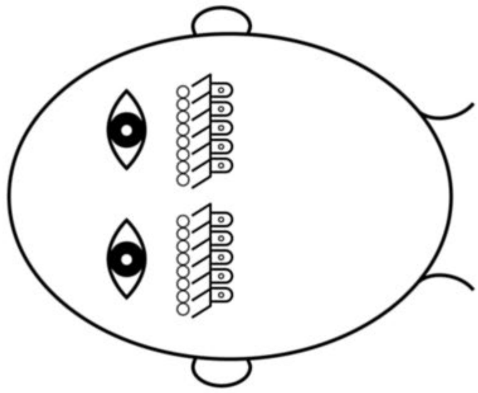

Figure 5: Maximising the angle of flexion of the cilia of the utricle can be easily achieved by lying in a lateral position. In the right lower lateral position, gravity pushes the cilia to the right. If the ocular counter-roll was the utricle ocular reflex, leftward torsional nystagmus should continue with this head position. However, nothing happens, which proves that nystagmus does not originate from the utricle.

The vestibulo-ocular reflex is a kind of spinal reflex, with gaze maintained by involuntary compensatory eye movements in the opposite direction to head rotation. Usually, the receptor for a spinal reflex is one organ, such as the cochlea for the stapedial reflex, and the retina for the pupillary light reflex. In the vestibulo-ocular reflex, if the receptors are two organs, the semicircular canals and the otolith organs, there will be two input systems, which will confuse the central nervous system. Semicircular canals are the only receptors for the vestibulo-ocular reflex, and the otolith organs are thought to be primarily involved in body balance.

Phylogenetically, otolith organs predate semicircular canals. For example, jellyfishes do not have semicircular canals, but they do have otolith organs [7]. Since primitive animals moved slowly, the otolith organs that sense gravity were probably sufficient. Later on, as vision evolved and the eyeballs began to move, semicircular canals became necessary to maintain vision, which is when the three semicircular canals were thought to have developed in order to control eye movements.

The role of the otolith organs is to sense gravity, and it is thought that this has not changed since the time of lower animals because the basic structure of the otolith organ is the same in all animals. The function of the semicircular canals differs from the otolith organs, which do not appear to be involved in eye movements.

Several researchers have attempted to evaluate the otolith organs' function using eye movements. Darlot, et al. [8] reported that horizontal nystagmus was induced by off-vertical axis rotation and speculated that it originates from the otolith organs. Sadeghpour, et al. [9] determined that the function of otolith organs can be measured by ocular counter-roll (torsional eye movements). It is unlikely that two types of nystagmus can be caused by one organ since the mechanism of stimulus perception is a simple movement, namely the flexion of cilia. Horizontal nystagmus and torsional nystagmus occurring at different times is highly improbable.

Ocular counter-roll caused by roll rotation can be explained if it originates in the semicircular canals rather than the utricles. There are three semicircular canals on each side, positioned so that they can sense angular acceleration in all directions of 360°. It is reasonable, therefore, to assume that the bilateral posterior and anterior semicircular canals are stimulated simultaneously during roll rotation, resulting in torsional nystagmus.

Although semicircular canals sense angular acceleration, our experiments showed that they do not respond to linear acceleration. Ichijo [10], speculated that the cupula receives inertial forces induced by linear acceleration. However, our results showed that this is incorrect and that the cupula only responds to angular acceleration.

Conclusions

Our results show that otolith organs do not cause nystagmus. Therefore, eye movements analysis cannot evaluate the function of otolith organs, and the ocular counter-roll is a semicircular canal ocular reflex.

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Conflict of Interest

We declare that we have no conflict of interest.

Funding

We declare that we have no funding.

Informed Consent

Informed consent was obtained from all subjects involved in this study.

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