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MASTER'S THESIS

MODELING THE DYNAMICS OF HUMAN OTOLITH ORGANS

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ABSTRACT

Key words: vestibular system, otolith organs, otolith membrane, head impulse test, videooculography.

The aim of this work is to investigate whether otolith organs can be activated during purely rotational movements during the head impulse test. Human otolith organs are the most important structural part of the vestibular system, responsible for the perception of linear accelerations of the head and gravity. Various tests are used to detect disturbances in the functioning of the vestibular apparatus: caloric, test on a rotating chair and head impulse test, all of which are aimed at diagnosing the function of the semicircular canals. At present, the head pulse test is the most common method of functional testing of six semicircular canals, which consists in a sharp forced turn of the head by 20-30 degrees at a speed of about 150-300 deg / s with simultaneous detection of eye movement.

However, this technique does not take into account the contribution of the otolithic organ to the reactivity of the vestibular system as a whole. It is believed that only semicircular canals are responsible for the perception of turns, although at such rates of head rotation, otoliths must inevitably experience centrifugal acceleration several times higher than the threshold values of their sensitivity of 0.08 – 0.14 m / s2[1].

Based on the results of the head impulse test on 50 healthy volunteers, an average graph of the head turn rate during the test was built. To process the data obtained during testing, as well as to calculate the magnitude of centrifugal forces applied to the otolith organs, the Matlab software package was used.

Based on the calculations, a hypothesis was build about the contribution of otoliths (utriculars) to the vestibulo-ocular response to head rotation at high speeds.

Main publications on the subject:

1. Abdykerimov A.D. Stimulation of the otolith organs during head turns //

Physical methods in natural sciences and materials science: Proceedings of the 58th Intern. scientific. stud. conf. April 10-13, 2020 / Novosib. state un-t. - Novosibirsk: CPI NSU, 2020. – P. 5–6.

2. Abdykerimov A.D., Demkin V.P., Pleshkov M.O. Activation of the otolith apparatus during the head impulse test // VII International Conference of Young Scientists: Biophysicists, Biotechnologists, Molecular Biologists and Virologists - 2020: Sat. thesis. / ANO "Innov. center Koltsovo ". - Novosibirsk: IPC NSU, 2020. – pp. 185–186.

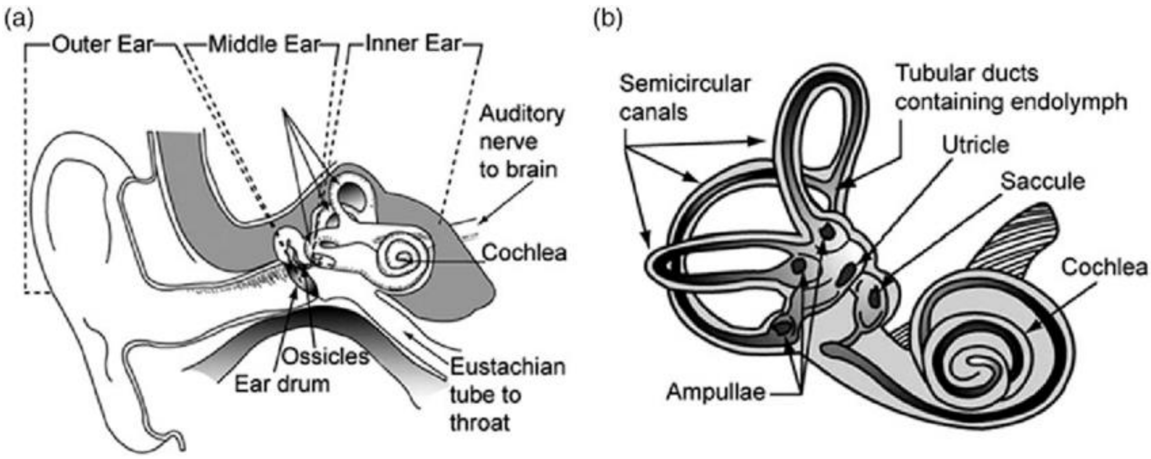
LIST OF ABBREVIATIONS

VOR –	Vestibulo-ocular reflex
HIT –	Head impulse test
vHIT –	Video head impulse test
OM –	Otolith membrane
MRI –	Magnetic resonance imaging
DICOM –	Digital Imaging and Communications in Medicine

TABLE OF CONTENTS

INTRODUCTION

In the process of evolution in living organism's life support systems were created for comfortable living on Earth, i.e. under conditions of gravity. The animal is forced to take a certain position in relation to the direction of action of the gravity, therefore, the digestive system, blood circulation and others are adapted to work in a certain position in relation to the vertical. A system for controlling the position of the body has also emerged: the vestibular system ensures the orientation of a living organism in the gravitational field of the Earth. The orientation of an animal in three-dimensional space under terrestrial conditions is based on information entering the central nervous system from at least four sensory formations. The otolithic organs of the vestibular system provide information on linear acceleration [1] and tilt relative to the gravity vector; information about angular accelerations is provided by the semicircular canals of the vestibular system; the visual system informs about the orientation of the body relative to the visual environment; the kinaesthetic system provides position information limbs of the body. The function of the central nervous system of the body is to integrate information about the environment received from different perception systems. The human organism consists of big amount of systems which work together and play their own role in maintaining the normal functioning of the whole body. A significant contribution to the regulation of the functioning of these systems is made by the autonomic (autonomous) nervous system - a division of the nervous system that controls the activity of internal organs, endocrine glands, external blood secretions, blood and lymph vessels and maintaining a balance not only vital powers but a physical as well.



(a) diagram showing the relationship of the vestibular apparatus to the external ear and skull. (b) Close-up of the vestibular organ showing the detectors for linear acceleration (the otolith organs-comprising the utricle and saccule) and the detectors for angular acceleration (the semicircular canals, one in each plane).

Figure 1 – Human vestibular apparatus

Constant balance is regulated by the cerebellum, which is attached to the brain stem immediately below the brain and is mainly responsible for motor activity. It sends signals that cause involuntary movements in the muscles, allowing you to maintain a pose and balance, and together with the motor parts of the brain provides coordination of body movements, but for the sensory ability to perceive the position of the head and the body responsible the complex receptor called – vestibular system. Vestibular system is a part of the labyrinth of the inner ear in most mammals and cochlea as part of the auditory system [2]. The otolith organs consist of two sacs: round and oval. These sacs are also filled with a viscous fluid, and they also contain receptor cells with cilia. Above the cells is a gel-like layer with small but rather heavy crystals of calcium carbonate - otoliths. When accelerated in one direction or another, the crystals are displaced and stimulate the receptor cilia. Otoliths allow us to feel where is up and where is down. In normal terrestrial conditions, information from sensory formations is compatible, mutually complementary and consistent with expectations based on previous experience. However, in non-standard situations (a sharp change in Vital activity is regulated by the activity of the nervous system. The nervous system functions through two main processes - excitation and inhibition reactions. It is very important to have a fine balance between these two processes. the speed of movement, being in microgravity conditions) or with diseases of the vestibular apparatus, the body cannot adequately perceive its position in space relative to other objects; information from the sensory system is three incompatible and inconsistent with existing in the nervous system incentive models. In such conditions, the so-called "sensory conflict"[3] develops (violation of inter-analyzer interactions), which is understood as the arrival of contradictory information passing along different sensory channels into the integrative structures of the brain. There are different points of view on the mechanism of this phenomenon: a) distortion of the incoming information at the receptor level is possible; b) the absence of a “nervous model of stimulus” in the integrative structures of the central nervous system; c) inadequate interpretation by the central nervous system sensory information changed in new conditions; d) inconsistency in time of adaptive processes in different sensory systems, etc. Some researchers believe that there is a "neural stimulus model" and a signal is perceived when the stimulus and the model match. "Sensory conflict" manifests itself in the development of abnormal motor and autonomic reactions of the body.

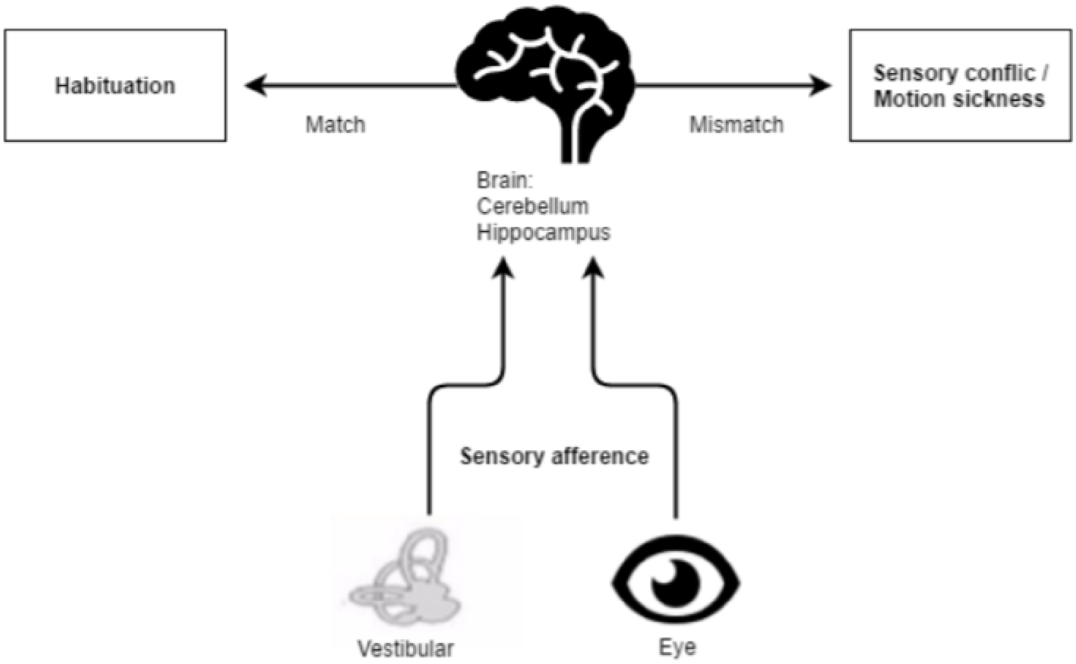


Figure 2 – Simplified version of Sensory conflict explanation diagram

When carrying out orbital flights in the initial and subsequent periods of stay in microgravity conditions, almost all cosmonauts note a number of specific sensations and autonomic reactions (symptoms of space motion sickness), in particular, orientation illusions, dizziness, coordination disorders, nausea, difficulty tracing visual objects in the field vision with visual control. Such sensations make it difficult and interfering with the fulfilment of the assigned tasks. In the conditions of the Earth, people with diseases of the vestibular system are poorly able to maintain balance, which leads to difficulties in movement or uncontrolled falls. Therefore, the task of analyzing the response of different sensory systems under the influence of a stimulus is urgent.

This work is devoted to the analysis of the reactions of the vestibular system. The vestibular apparatus plays a leading role in the perception of information about the accelerations acting on the body, and is the first to react to any changes in external stimuli (in the form of changes in accelerations) (reaction time about 50 100 ms). The visual and kinesthetic systems then react. Information from the vestibular system enters the central nervous system, and after processing and comparison with information from other body systems: visual, tactile, proprioception systems, commands are sent to muscles to correct body position.

So the main research question is How are the otolith organs stimulated by turning the head and Research problem is Role and function of the otolith organs to the vestibular response.

This work will investigate the reactions of secondary mechanoreceptors: semicircular canals and otolith organs. vestibular apparatus (channel otolithic reaction). By vestibular reaction we mean a change in the membrane potential of a receptor cell under the action of a mechanical stimulus. The subject of analysis is the information that comes from the secondary mechanoreceptors for transmission to the central nervous system in response to the given gamules, i.e. membrane potentials of the cells of the semicircular canal and the otolith organ. In case of mismatch between signals from two complexes of the vestibular system of the semicircular canals and otolith organs, inadequate reactions occur in a living organism, which manifests itself in the form of dizziness, nausea, visual illusions, and motion sickness develops. Lesions of the vestibular system lead to loss of balance (violation of the vertical posture), difficulty with orientation, leading to disability. Difficult meteorological conditions in the absence of visual reference points and the effect of overloads cause the emergence of the illusion of spatial position in pilots in flight.

It is important to learn how to predict the response of the vestibular apparatus to extreme stimuli. For this, the simplest way seems to be the way of creating mathematical models of the vital activity systems of a living organism and conducting computer experiments to analyse the behaviour of the system. before or in parallel with field experiments. There are mathematical models of individual physiological structures and processes that are used by the body to transmit vestibular mechanical stimulus information system. The complexity of the models developed takes into account the details of the morphology and physiology of the vestibular system. There are also mathematical models of the entire conversion process stimulus information into signals about body position, but in these models there is no correspondence to the physiological mechanisms of processing information about the stimulus. But there is no complete model that describes consistently real biological processes in the vestibular apparatus during the transformation of a mechanical stimulus into electrical impulses that propagate along nerve fibres.

The paper proposes a mathematical model for processing information about a mechanical external stimulus for the semi-circular canal and the otolith organ, which sequentially describes the biological structures used to transmit information about the stimulus. A technique for identifying the parameters of the presented model using experimental data has been developed. Numerical experiments have been carried out for some types of stimuli using model parameters identified using experimental data. The results of the considered experiments allow us to say that the presented mathematical model of the acantholytic reaction can be used to analyse the vestibular function in extreme conditions of bionavigation and in the development and creation of vestibular prostheses. This model can be used to predict the body's response in non-standard situations, to stimuli that are difficult to create during experiments on existing simulators. To carry out numerical modeling, it is necessary to create a mathematical model of the channel of the otolithic response to the input stimulus. Turning the head at a constant speed at a certain angle, falling of the body, staying in microgravity conditions, and others can be selected as an input stimulus. It is proposed to construct a simplified mathematical model of the otolith reaction channel. The model consists of blocks that have physiological meaning and correspond to real processes along the path of passing information about an external stimulus from receiving a signal to converting it into electrical impulses and responses to a stimulus in mechanoreceptors of the vestibular system: semicircular channel and otolith organ.

A mathematical model of the dynamics of the otolith membrane is described in the case of representing the movement of the otolith membrane as the movement of an absolutely rigid body. The otolithic membrane can be modeled as a first approximation as an absolutely rigid body for a limited class of animals, in particular for amphibians [4].

Human otolithic organs are the most important structural part of the vestibular system, responsible for the perception of linear accelerations of the head and gravity. Like any other organ in the human body, the vestibular system and its structural parts are subject to certain factors that can lead to dysfunction of the balance organ and, as a result, the person’s loss of a sense of balance, both static and in motion. As is known, a receptor is understood as a highly specialized formation containing receptor cells capable of perceiving, transforming, and transmitting the energy of an external stimulus to the nervous system. Mechanoreceptors are a large group of receptors in which the processes of perception and transformation of external influence occur under the condition of mechanical displacement or deformation of the receptor site. All receptors are divided into primary sensing (primary) and secondary sensing (secondary). In the primary receptors, the perception and transformation of the energy of irritation into the energy of nervous stimulation occurs in the most sensitive neuron. Secondary receptors between the stimulus and the first neuron is a highly specialized receptor cell, i.e. the first neuron is excited indirectly through the receptor cell. In particular, tissue mechanoreceptors belong to primary, and hair cells of the vestibular apparatus - to secondary mechanoreceptors. Consider the accumulation of hair receptor cells on sensitive elevations of the otolith organs of the vestibular apparatus (macula sacculi, macula utriculi) For simplicity, a set is shown that consists of an otolithic membrane containing calcium crystals and one hairline glue. In what follows, we will call this set the gravito-inertial[5] mechanoreceptor. To justify this name, let us find out the nature of the mechanical stimulus for a given the aggregate. Consider movement the otolithic membrane along the x axis of the hair cell.

The aim of the work was to propose a mathematical model of the otolith reaction channel with parameters that have a physiological meaning, which describes the real processes of transformation of information about the stimulus by mechanoreceptors. Develop a technique for identifying model parameters using experimental data. Consider the reactions of two different mechanoreceptors (semicircular canal and otolith organ) of the vestibular system to mechanical stimuli (turns and the gravitational acceleration), compare these reactions and estimate the time required for each of the sensors to generate a response. Mathematical model of the channel of the otolith response to a stimulus in the form of angular and linear accelerations has been built. Each block of equations of the model has a physiological meaning, as well as the parameters of the model, which can be identified for a specific organism using data from morphological and physiological experiments. A complete mathematical model of the channel of the otolith response to a mechanical stimulus was obtained, corresponding to the real stages of the process of transformation of a mechanical stimulus that occurs in the secondary mechanoreceptor.

In accordance with the aim, the following tasks were set:

– studying of COMSOL Multiphysics program package and VOG working principles;

– built mathematical model of otolith membrane deformation

– studying the way of the Head Impulse Test running;

– learning how to make and perform the Head Impulse Test in a group of volunteers using VOG method

– analyze VOG signal and process the MRI images for physical measuring;

– statistical analysis methods selection;

1 Literature review

1.1 Frequency responses of otolith organs

Dependence of the calculated frequency response on the mass of the saccular otolith is shown in figure 3. Calculations were performed for the frequency range of acoustic waves from 10 to 10000 Hz, the range of otolith masses from 0.01 to 100 mg, and a constant amplitude of displacement of water and the body of the fish is equal to 1 μm. It could be Fig. 10 shows that the otolith / macula system is almost critically damped. The sensitivity (the amplitude of the displacement of the otolith relative to the macula per unit of water and the amplitude of the displacement of the fish body) increases with an increase in the mass of the otolith (Fig. 3). The frequency at which the amplitude of the otolith displacement is maximum shifts υmax towards low frequencies with increasing mass of the otolith (Fig. 3). At frequencies well above υmax, there is no dependence of the amplitude of the displacement of the otolith on the mass of the otolith. Generally, the greater the mass of the otolith, the higher the sensitivity to low frequencies and the sharper the frequency-response curve at frequencies around υmax. The above conclusions are also relevant for the lagena otolith. Primary central processing of signals from the peripheral vestibular system occurs in the vestibular nuclear complex and in the cerebellum. The vestibular nuclear complex carries out the main processing of incoming vestibular signals and realizes direct, fast connections between incoming afferent information and efferent motor responses. The cerebellum processes and adapts vestibular information. It monitors the vestibular system and, if necessary, corrects the central vestibular processing. In the vestibular nuclei and cerebellum, vestibular sensory information is processed in a comprehensive manner in combination with somatosensory and visual afferent information

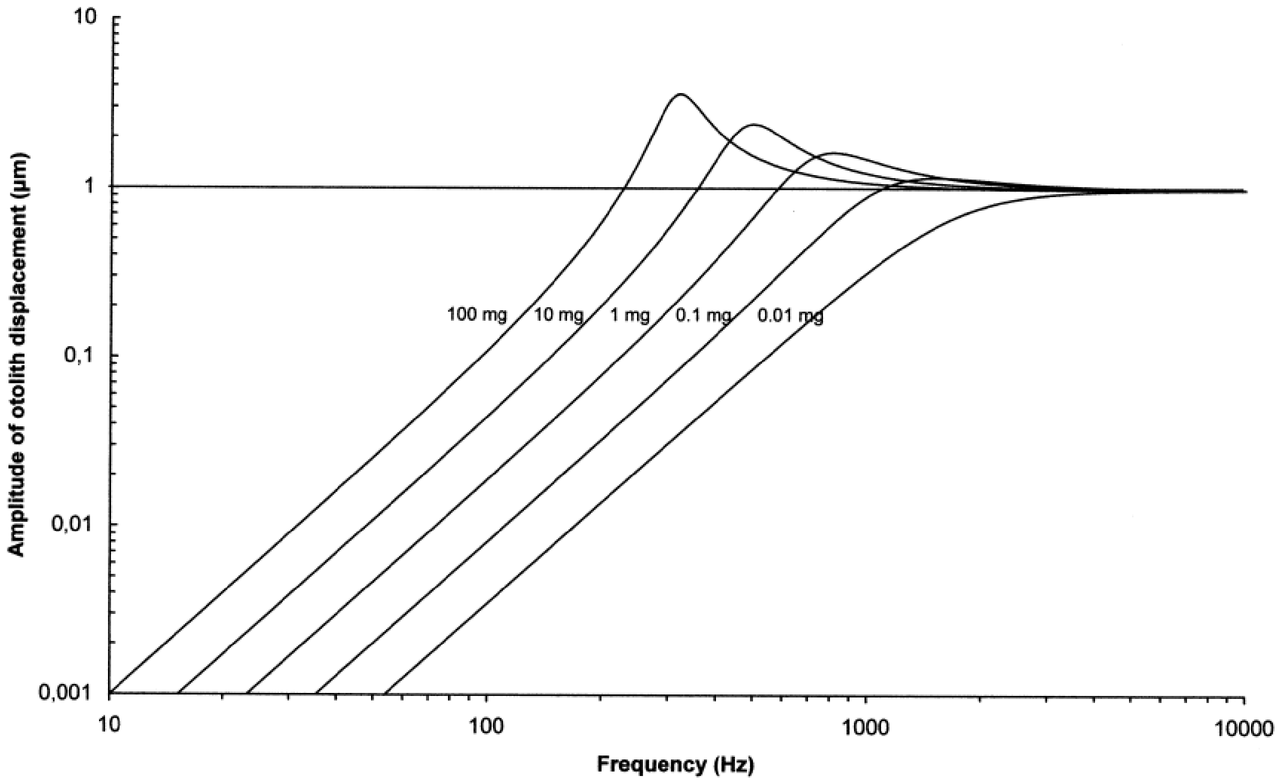


Figure 3 – The calculated frequency responses of the otoliths of different masses[6]

Based on the above assumptions and using the morphometric rules of the otolith, we can trace the functional characteristics of the otolith at different depths. this is it is very convenient that the relative displacement of the otolith can be expressed in terms of one variable, i.e. otolithic mass. The development of studies of the function of the otolith and the improvement of the experiment have led in recent years to the emergence of new directions in modeling the otolith as a system with distributed parameters associated not only with the mechanical, but also with subsequent stages of information transformation in the otolith. At the same time, the improvement of the models of the stage "physical stimulus - deformation of the otolith membrane" continued. Vestibular hair cells are very similar to auditory hair cells, but the vestibular sensory "superstructures" - the otolithic membrane or cupula - are so different that the question arises as to how the otolith and afferents of the canal can exhibit phase synchronization up to such high frequencies. Similarity of precision of phase locking in otolith and canal systems may lie in the fact that it is fluid displacement to both systems that deflects the hair cell hair bundles. Species with only type II vestibular hair cells (fish and frogs) shows phase synchronization, but usually it is lower frequency than mammals[7].

The formation of the reaction of otolith afferents to the displacement of the otolith membrane under the action of acceleration occurs in several stages, one of which is the processing of information received by MRI belonging to one terminal field. Such an "integrated" the response of the terminal field is responsible for modulating the afferent state. The process of processing and comparison of signals from a VC of a given afferent occurs, apparently, due to the local neural network carrying out morphological and informational interaction between these VCs, but the mechanism of this interaction before is still unclear. Based on opportunities computer reconstruction of the morphology of receptor formations and their connections within the terminal field according to the data of electron microscopy of ultrathin parallel sections of the structure, it turned out to be possible to create volumetric three-dimensional image of MRI and their local connections [8] in modeling, an attempt was made to use the obtained detailed information on the internal structure of the receptor fields for computer modeling of electro-physiological processes occurring in a given receptor-neural system. These processes included the propagation of electric polarization in the calyx surrounding a group of type I cells, the effect on this potential of synaptic contacts with type II cells; geometric dimensions of calix and neurons, the effect of myelination of nerve fibers, taking into account the nonlinearity of the model of the propagation of a nerve impulse (Hodgkin - Huxley model), and a number of other factors. Despite the complexity of the task and the uncertainty of a number of structural parameters and processes - objects of modeling, the results of the work made it possible to make assumptions about the nature and principles of information exchange in a given local network, as well as to try, on the basis of structural data, to formulate the tasks facing with such a processor [9].

1.2 Video oculography in diagnosis of vestibular system

Video eye tracking is the most widely used method in commercial instruments. Until recently, gaze tracking was an extremely difficult and costly task. which was limited to laboratory research only. However, rapid technological advances such as increased processor speed, modern digital video processing technologies have lowered the cost and significantly increased the efficiency of eye tracking equipment. In video oculography, one or more cameras are used to detect eye movements using information obtained from recorded images. Eye tracking video systems can be aggressive and non-aggressive towards human eyes. Each type of system is divided into two categories depending on the type of light source used: visible light or infrared light. Active systems, or systems installed on head, usually consist of one or more chambers. Most types of eye trackers work by illuminating the eye with an infrared light source. The light forms a flare on the cornea of the eye and is called corneal reflection. In most of the published work, the lens flare is used as a reference point for gaze measurements. The pupil-flare difference vector remains constant when the eye or head moves. Glare obviously changes position when moving head, the direction of sight changes. But it is less obvious that the lens flare shifts to a different position when the direction of the gaze changes. Head impulse test provides quick identification and assessment of the degree of damage to the vestibulo-ocular reflex (VOR) in response to stimuli in the high-frequency range, which is natural for head movements. This is the only test that can assess the functionality of all six semicircular canals. Otometric`s ICS Impulse® System is the world's first vHIT device that combines gold standard precision with unmatched patient comfort, enabling impulse head testing with undeniable results. The ICS Impulse System, fast, simple and accurate, is recommended as a first step in your analysis, helping you improve your workflow and spend more time caring for the patient.

Figure 4 – Video eye tracking system placed on subject’s head

The main disadvantage of all of these systems with a fixed single camera, there is a limited field of view required to capture high-resolution, high-quality images. Adding multiple lights the installation will provide the best results, than with a single source. In addition to the high accuracy and objectivity of measurements of the VOR, the ICS Impulse system allows testing patients with spontaneous nystagmus. The system allows detecting explicit and hidden overtaking saccades, which allows correct diagnosis and prescription of treatment.

The angular acceleration of a head impulse up to 400°/s2 - is what occurs during normal head movements. A head impulse is a purely vestibular test because it is too fast for other oculomotor control systems.

Using similar methods, the researchers were able to estimate the relative contribution of otoliths, or channels in cats[10] and in humans[11]. This interaction is considered particularly important in research. the vertical vestibulo-ocular reflex, which usually occurs in a plane aligned with gravity. Vertical optokinetic nystagmus may share pathways as it has been shown to be modulated macular ablation in monkeys[12] and static head tilt in monkeys and humans[13], indicating otolith entry into optokinetic mechanisms.

1.3 Inner ear structure

If we look to the otolith organs we can see that they have composite structure consisting of hair cells – the mechanoreceptors which are rooted into the jelly called otolith membrane and on the top of it the layer of otoconial calcium carbonate bodies. So this system is very close to the critical damped pendulum.

The response to gravity is very important for the Homo erectus. Not only humans, but also animals and plants react to gravity. Man, animals and plants know exactly where is up and where is down. Plants can determine this because there are cells in the root cap that contain leukoplasts, these leukoplasts precipitate and press on the membrane of the root cap cells. The plant is precisely oriented towards the center of the earth. And this allows the plant to properly direct the growth of the root and stem.

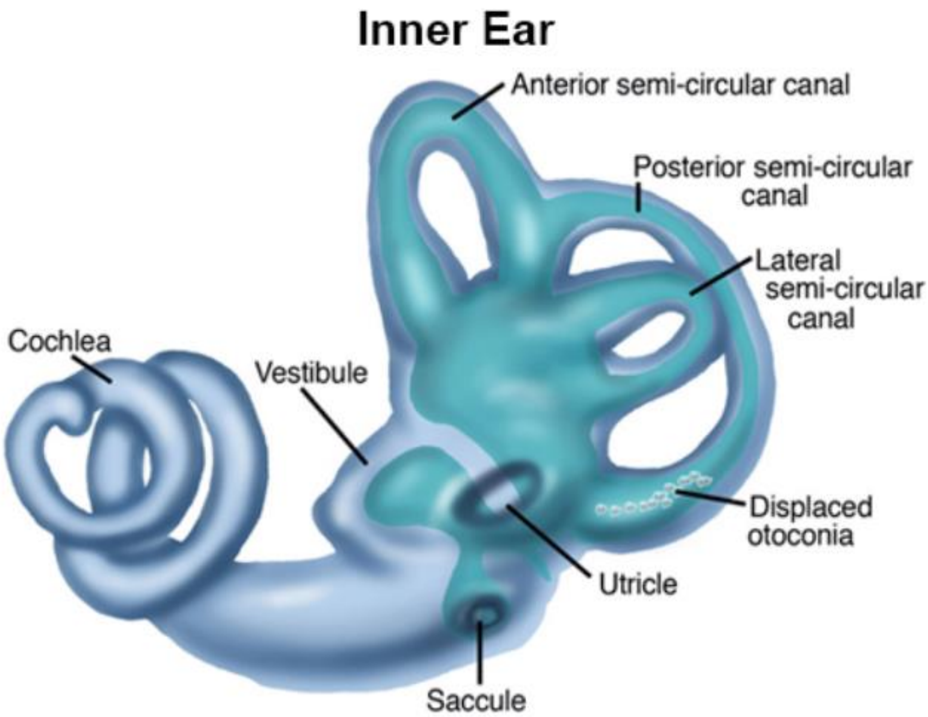


Figure 5 – The inner ear is the innermost part of the vertebrate ear

In humans, the vestibular system works differently. It works through the function of hair receptors in the vestibular part of the inner ear. Hair receptors respond to mechanical bending of hairs. Our inner ear, as a structure, is located inside the bone mass of the temporal bone. The inner ear contains a cochlea, two vestibular sacs and three semicircular canals. These sacs and channels are filled with endolymph, which contains a lot of potassium ions. An excess of potassium in the endolymph is not quite standard for the body, since there is usually an excess of sodium in the intercellular environment, and there is a lot of potassium in the cytoplasm. This difference in sodium and potassium underlies many electrical processes in our nerve and muscle cells. In endolymph, the generation of electrical excitation occurs due to the input of a positively charged potassium ion, which excites hair receptors and further generation of an electrical impulse in the eighth cranial (vestibular cochlear) nerve. In order to respond to movement with acceleration in the vestibular sacs there is a structure called a jelly-like mass. There are many of these hairs, about three thousand in each vestibular sac, and on these hairs a jelly-like mass neatly lies, which is slightly denser than the endolymph. The density of the jelly-like mass is very precisely regulated by mineral crystals, the so-called otoliths. Interestingly, these otoliths are composed of calcium carbonate, although the main mineral in our bodies, such as bones, is calcium phosphate. And here is calcium carbonate, which is more typical, for example, for mollusks.

When the function of one vestibular labyrinth (right or left) is suddenly reduced due to an accident, infection, or surgery, the person tends to fall on the injured or painful side. However, this symptom lasts only a few days, even in cases where the function of the affected side is not restored. The reason for this recovery, and a similar decrease in other symptoms, lies in the powerful self-healing or adaptive capacity of the vestibular system. The main therapeutic approach to vestibular deficits is self-learning. In the first weeks after a sudden loss of vestibular function, the patient is trained using general natural body movements; in the following weeks, special training for impaired functions and symptoms is required.

The vestibular nerve is an afferent fiber from the bipolar neurons of the Scarpa vestibular ganglion. It passes through the internal auditory canal, through which the cochlear nerves, facial nerves, and the labyrinth artery also pass. The internal auditory canal is located inside the petrosal part of the temporal bone and opens into the posterior cranial fossa at the level of the bridge. The vestibular nerve enters the medulla at the level of the bridge junction into the medulla oblongata. At this point, the myelin sheath of the nerve is the thinnest, which makes the nerve most vulnerable in this area. At the level of the rhomboid fossa in the medulla oblongata, vestibular the nerve forms ascending and descending branches. Part of the descending fibers ends in the lower core. Another part of the descending fibers goes to the medal and lateral nuclei. The ascending fibers are directed to the upper the core[14]. There are two types of excitation transmission in the vestibular nerves. Typical afferent fibers are characterized by tonic activity and little variability in the inter-peak intervals. In atypical afferent fibers, there is often no excitement in at rest, and when they are stimulated by head movement, there are significant variations in the intervals between the peaks. Typical afferent fibers are the most important for ensuring the vestibulo-ocular reflex, since in experimental animals, atypical afferent fibers can be removed without significant changes in the vestibulo-ocular reflex. Atypical afferent fibers provide coordination responses between otolithic organs and semicircular canals[15]

It was previously shown that of all the experimental models used on Earth, immersion[16] is the most adequate from the point of view of analogy of sensorimotor reactions with reactions observed under zero gravity conditions. Immersion itself does not directly affect the vestibular receptor, but it creates support unloading and minimizes muscle activity, i.e., in other words, reduces the influx of supporting, tactile and proprioceptive afferentation into the integrative structures of the central nervous system, where multisensory convergence of afferent signals of different sensory modality occurs, primarily visual, vestibular, motor and support. Thus, immersion, without directly affecting the visual and vestibular receptors, nevertheless, changing the level and nature of the supporting, tactile and proprioceptive afferentation, through the central integrative multisensory structures of the central nerve system, converging afferent signals of different sensory modality, can lead to a change in the nature of the functioning of multisensory vestibular nuclei and activating structures of the middle brain. Apparently, under immersion conditions, the elimination of support and a decrease in tactile-proprioceptive afferentation is accompanied by the development of inhibitory influences going along the efferent nerve fibers from neurons located in the vestibular nuclear complex, the reticular formation of the pons and medulla oblongata and cerebellum, which lead to suppression of otolith afferentation[17].

1.4 Conducting path of balance and gravity analyzer

A nerve impulse that occurs in the hair cells of an organ balance and gravity during endolymph vibrations, is transmitted to the receptors of peripheral processes (dendrites) of the first sensitive neurons. The bodies of these neurons are laid in the vestibule node, ganglion vestibulare, at the bottom of the internal auditory canal. Axons of sensory neurons form the vestibular part of the vestibular cochlear not ditch, which includes the cranial cavity through the internal auditory meatus and further, at the posterior edge of the bridge, lateral to n. facialis, enter into the substance of the brain. Here, the axons of the first neurons form the ascending and descending branches and approach the vestibular nuclei located in the lateral corners of the rhomboid fossa in the vestibular field, the area vestibular

On each side there are 4 vestibular nuclei:

1. Upper vestibular nucleus (ankylosing spondylitis).
2. Lateral vestibular nucleus (Deiters nucleus).
3. Medial vestibular nucleus (Schwalbe nucleus).
4. Lower vestibular nucleus (Roller's nucleus).

The ascending branch ends in the upper vestibular nucleus, and the descending branch ends in the other three. In the vestibular nuclei, the bodies of the second neurons are laid, the axons of which go in the following directions:

1) to the cerebellum - the vestibular cerebellar pathway (tractus vestibulocerebellaris);

2) to the spinal cord - the vestibular spinal path (tractus vestibulospinalis);

3) as part of the medial and posterior longitudinal bundles (fasciculus longitudinalis medialis, fasciculus longitudinalis posterior);

4) to the thalamus of the opposite side - the vestibule-thalamic path (tractus vestibulothalamicus).

The vestibular pathway passes through the lower leg cerebellum and ends on the cells of the cortex of the cerebellar vermis. Part of the axons of sensory neurons does not switch in the vestibular nuclei, but follows directly into the cerebellum. There is also a feedback of the cerebellum with the vestibular nuclei in the form of the cerebellar vestibular tract, tractus cerebellovestibularis, through which the cerebellum has an indirect effect on the spinal cord along the vestibular pathway. The fibers of the vestibular-spinal tract end severally mentally on motor neurons in the anterior horns of the spinal cord. It conducts motor impulses to the muscles of the neck, trunk and extremities, providing unconditional reflex maintenance of body balance during vestibular loads.

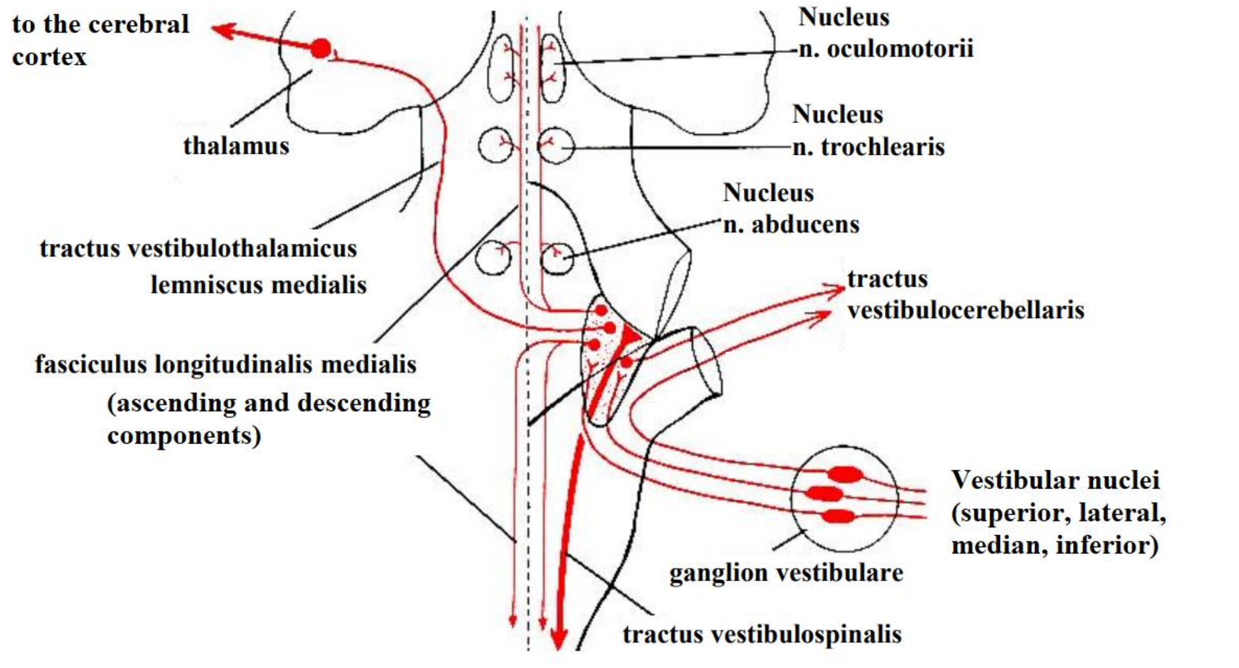


Figure 6 – Diagram of the pathway of the vestibular apparatus

Part of the axons of the Deiters nucleus cells are directed as part of the medial longitudinal bundle of their own and opposite sides and end on the cells of the intermediate nucleus and the nucleus of the posterior commissure. These nuclei of the reticular formation of the midbrain provide a connection between the equilibrium organ and the nuclei of the cranial nerves (pairs III, IV, VI), which innervate the external muscles of the eyeball and the muscles of the neck. This allows you to maintain the direction of gaze when changing the position of the head. Part of the axons of the cells of the nucleus of Deiters enter into the composition of the posterior longitudinal bundle and end on the cells of the posterior hypothalamic nucleus. This nucleus provides a connection between the organ of balance and the autonomic nuclei of the cranial nerves (III, VII, IX, X pairs). Therefore, with excessive irritation of the vestibular apparatus, autonomic reactions often appear in the form of a slowdown in the pulse, a drop in blood pressure, nausea, vomiting, pale skin, cold extremities, increased secretion, etc. Part of the axons of the cells of the vestibular nuclei pass to the opposite side and form the vestibular thalamic pathway. It ends in the thalamus, where the bodies of third neurons lie. Their axons go through the posterior leg of the inner capsule to the cerebral cortex. It is believed that the cortical end of the vestibular analyzer is localized in the region of the middle and inferior temporal gyri. In the cerebral cortex, there is a conscious assessment of vestibular stimuli: determination of the position of the head, the degree of inclination of the body in space.

1.5 Dynamics of otolith organ

All receptors are divided into primary sensing (primary) and secondary sensing (secondary). In the primary receptors, the perception and transformation of the energy of irritation into the energy of nervous stimulation occurs in the most sensitive neuron. At the secondary receptors, between the stimulus and the first neuron, there is a highly specialized receptor cell, i.e. the first neuron is excited indirectly through the receptor cell. In particular, tissue mechanoreceptors belong to primary, and hair cells of the vestibular apparatus - to secondary mechanoreceptors.

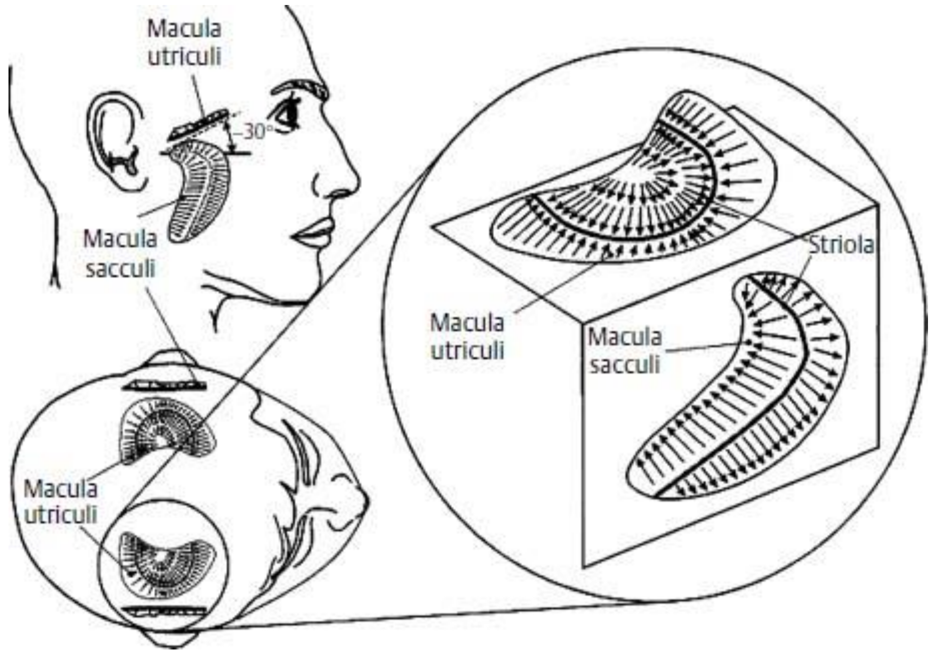


Figure 7 – Orientation of the otolith organs. The utricle is oriented roughly perpendicular to gravity and the saccule lies parallel to gravity when the subject is upright

The results of experimental studies over the past ten years [18] have shown that, in contrast to the gravito-inertial sensor existing in technology (accelerometer), the gravito-inertial mechanoreceptor does not measure the apparent acceleration, but only reacts to it, supplying information to the nervous system, nonlinearly dependent on mechanical stimulus. The nonlinearity of the reaction is expressed primarily in the presence of the property of adaptation.

The absence of gravity in space flight leads to a change in afferentation from gravitationally dependent sensory inputs: otolith receptors and support zones of the foot. To understand the role of this or that etiological factor in the development of perceptual and sensorimotor disorders developing under zero gravity, it is advisable to carry out comparative studies in model experiments.

Consider the accumulation of hair receptor cells on the sensitive elevations of the otolith organs of the vestibular apparatus (macula sacculi, macula utriculi) for simplicity, a set is depicted, consisting of an otolith membrane containing calcium crystals and one hair cell, movement of the otolith membrane along the x axis of the hair cell. Assuming the rigidity of the otolith membrane (in fish, amphibians, etc.), the equation of motion of its center of mass along the axis of sensitivity has the form:

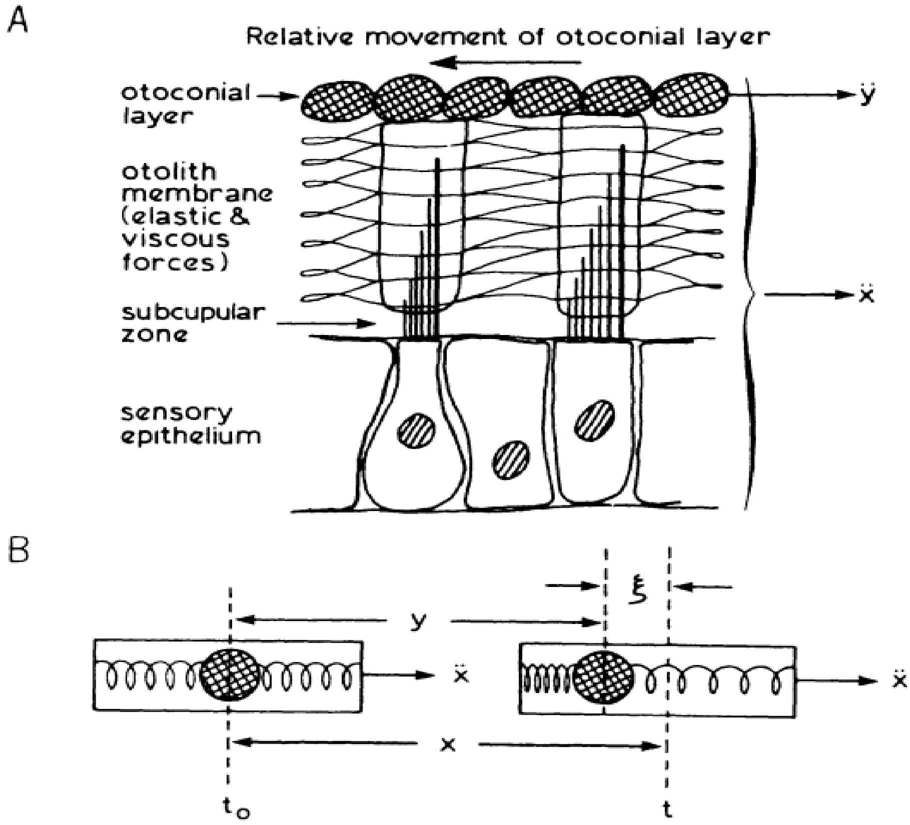


Figure 8 – Otolith organ structure and critical damped pendulum

$$\left(1-\frac{\rho_e}{\rho_m}\right)\ddot{x}=\ddot{\xi}+\frac{B'}{m}\dot{\xi}+\frac{K'}{m}\xi \tag{1}$$

Where $\ddot{x}$ = linear acceleration of the whole system; B' = viscous drag coefficient; K' = spring coefficient; m = equivalent mass of otoconial Body; ξ = relative displacement of the otoconial body (i.e., the response of the sensor); ρ_e = density of endolymph; ρ_m = density of the otoconial body.

It can be seen from the equation (1) that the external forces are the gravitational force and the force of inertia, which allows this secondary mechano-receptor to be called the gravitational-inertial mechanoreceptor. Due to the elastic connection of the kinocilium (supporting hair) with the otolith membrane, when the latter is displaced, deformation of the kinocilium and all sensitive hairs, called stereocilia, occurs. The stereocilia are connected by lateral elastic bonds located along the axis of sensitivity.

As follows from the results of the research[19], the channel located in the stereocilium, it occurs with the help of an apical elastic connection connecting the movable "gate" of the ion channel with the apex of the adjacent stereocilium. Let us consider, as an example, one of the stereocilia closest to the kinocilium and the neighboring stereocilia (Figure 9).

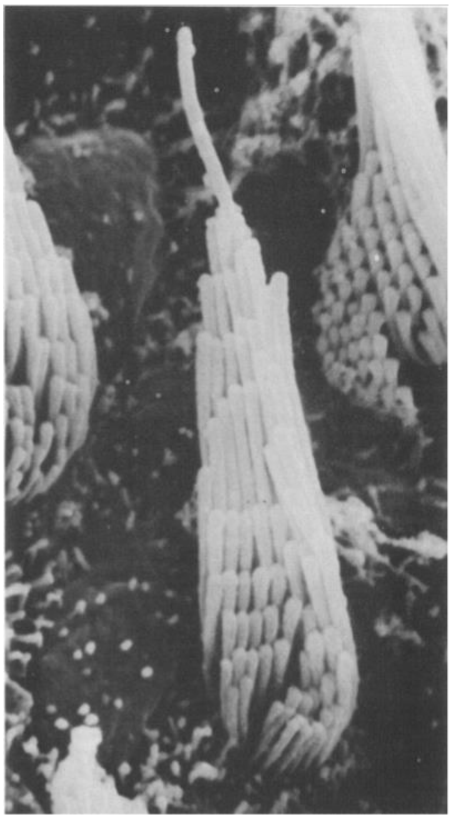


Figure 9 – Hair cell [20] located at the distal end of the cochlea has 50 stereocilia, the longest of which are 5.5 microns in length and 0.12 microns in width, while those at the proximal end number 300 and are maximally 1.5 microns in length and 0.2 micron in width.

The otolith membrane, due to morphological polarization, makes it possible to obtain information about the apparent acceleration of the head in many directions. In the dissertation, only one axis S of sensitivity was chosen along which the greatest response of hair cells to a mechanical stimulus, leading to a fall of a person in the sagittal plane, takes place. This axis is located in the sagittal plane and is orthogonal to the local vertical of the person at the initial moment of the fall.

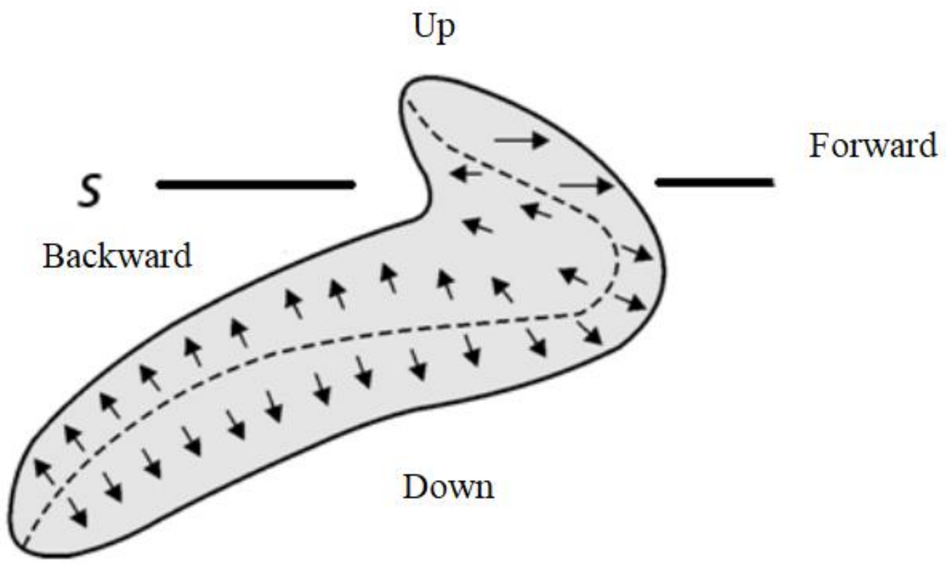


Figure 10 – Diagram of the macula of the sacculus with the directions of the sensitivity of the hair cells. The dotted line represents the striola

Gravito-inertial mechanoreceptor means the main specialized formation of the otolith apparatus, described by a set of three mathematical models, the first of which describes the dynamics of the otolith membrane along the considered S axis of sensitivity, and the other two describe the response to the displacement of the otolith membrane of two vestibular mechanoreceptors opposite positive directions located in different directions relative to the striola (Figure 10). Running, flying and swimming vertebrates move along their longitudinal axis. At the same time, the head of a running four-legged vertebrate animal, placed on a rather long, flexible neck in the vertical plane, practically does not participate in vertical oscillations together with its body. Due to the control of the muscles of the neck, the head is kept practically in the plane of the horizon at the same level. It plays the role of a stabilized platform[21], on which lies a movable rather massive otolithic lenticular body (test mass) of the utriculus, connected by elastic hair tips with its numerous mechanoreceptors. The utriculus is an otolithic organ located in the head, in the inner ear of a vertebrate animal (in its vestibular apparatus). Mechanoreceptors of the utriculus are laid on its horizontally located epithelium, forming a closed sensory surface (matrix), repeating the rounded shape of its otoliths[22].

In the case of prolonged deflection of the stereocilia as a result of the action of a mechanical stimulus, the elongation of the apical connection decreases due to the shift of the right end along the considered stereocilia, which leads to a double effect: the possible closure of the canal, which means a decrease in the transduction current, and a simultaneous decrease in the rigidity of the apical elastic connection[23]. This becomes possible due to the action of the actomyosin motor located inside the stereocilium[24]. In turn, this action becomes possible due to the reaction of the calmodulin protein to an increased calcium concentration in the transduction current. Thus, in this situation, calmodulin acts as a sensor and regulator. For a mathematical description of the dependence of the response of the hair cell simultaneously on both the mechanical stimulus and the effect of the considered feedback, one can pass in the equation from an argument to a new argument - the lengthening of the apical connection , which, in turn, is a function of two arguments, $\Delta = \Delta\,(x_1\,, \alpha)$, where $\alpha = \alpha(t)$ is the feedback parameter, which is the displacement of the upper right end of the apical elastic connection relative to some initial position. The corresponding Laplace transfer function is given by:

$$\frac{\xi}{\ddot{x}}(s) = \left(1 - \frac{\rho_e}{\rho_m}\right) \cdot \frac{1}{s^2 + (B'/m)s + K'/m}$$
$$= \left(1 - \frac{\rho_e}{\rho_m}\right) \cdot \frac{m/K'}{(T_1 s + 1)\,(T_2 s + 1)}$$

where $T_1 T_2 = m/K'$ and $T_1 + T_2 = B'/K'$. (2)

The equations describe the dynamics of the otolithic membrane and hair bundle. These ratios can be considered as a biomechanical block of the functional diagram of the gravity-inertial mechanoreceptor, which is under the influence of an external mechanical stimulus and an internal control force that changes both the mechanical characteristic - the elongation of elastic bonds - due to the shift of attachment points, and the conductivity of the hairline. beam by opening or closing ion channels. However, while the simplicity of the elementary canal mechanics allows one to numerically estimate the relevant parameters and hence analytically predict likely dynamic response patterns[25], this is not possible for a complex mechanical system of the otolith organ. On the one hand, the "effective" mass of the otoconium-otolith junction of the membrane-cilia assembly is not easy to assess. On the other hand, an uneven surface in the voids of the otolith membrane mesh and completely unknown frictional forces that can arise inside it, deny the possibility of calculating the coefficient of viscosity. Therefore, we need to move to an experimental rather than an analytical approach to further understand the response of the end organ. The vestibular apparatus consists of two types of receptor formations: otoliths that respond to linear accelerations and semicircular canals that perceive angular accelerations of the head. The way of transforming information about a mechanical stimulus both in the semicircular canal and in the otolith organ is fundamentally the same. As a result of the action of inertial forces, the sensitive mass of the sensor (cupula and endolymph of the semicircular canal or the otolithic membrane of the otolith organ) is displaced relative to the surface of the sensory epithelium (cristae of the semicircular canal or macula of the otolith organ), as a result of which the hair bundles of receptor cells are deflected. This leads to a change in the membrane potential of the hair cells themselves, which in turn, through synaptic transmission, modifies the frequency of afferent impulses of primary neurons. Thus, information about head movement is converted and transmitted to the vestibular nerve. The set of one type II hair cell and a primary afferent neuron, connected by synaptic transmission, is commonly referred to in the thesis as the vestibular mechanoreceptor. This formation is the basic element of the vestibular apparatus.

1.6 Head impulse test

The head impulse test is one of the generally accepted methods for diagnosing the vestibular apparatus. During the test, a rapid turn of the head of a small amplitude occurs, which in turn causes a vestibulo-ocular reflex - movement of the eyes in the direction opposite to the movement of the head. Vestibular function is assessed based on the pattern of eye movement relative to head movement. The method of registration of eye movements is based on the detection of the image of the pupil in the frame, based on the contrast of the image between the pupil and the iris. This contrast is higher when the eye is illuminated with infrared light[26]. The advantages of the method are its non-invasiveness and a wide range of characteristics of eye movements available for study. In a number of the described works, eye movements were recorded using eye trackers, allowing to create comfortable research conditions for the patient and efficiently process the obtained oculograms. In HIT, the doctor abruptly and unpredictably turns the patient's head in the horizontal plane by about 15 ° in about 100 ms and observes an instant compensatory eye movement response. During each impulse of the head, the response of the eye movement of a healthy person will compensate for the rotation of the head, and the gaze will remain fixed on a target fixed on the ground. A common measure of the adequacy of the vestibulo-ocular response (VOR) is amplification. Gain is a general term for the ratio of output to input in any dynamic system. To measure the VOR gain, we calculate the ratio of the area under the eye velocity curve to the area under the head velocity curve during the head pulse.

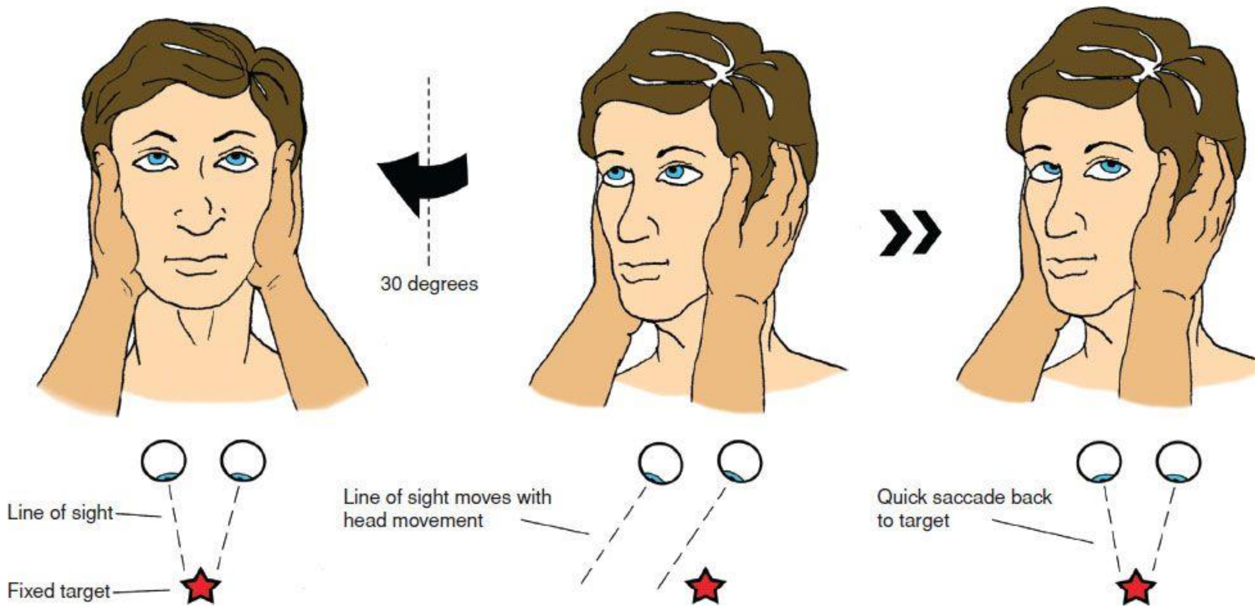


Figure 11 – The head impulse tests the vestibulo-ocular reflex and can help to distinguish a peripheral process from a central one

To detect deviations in the functioning of the vestibular apparatus, various tests are used: caloric, a test on a swivel chair and a head impulse test[27], all of them are aimed at diagnosing the function of semicircular canals. Currently, the head impulse test is the most common method of functional testing of six semicircular canals, consisting in a sharp forced turn of the head from 15 to 30 degrees at a speed of about 150-300 degrees / second with simultaneous detection of eye movement. However, this technique, in the way it was formed, does not consider the contribution of the otolith organ to the reactivity of the vestibular system as a whole. It is believed that only semicircular canals are responsible for the perception of turns, although at such head rotation speeds, otoliths should inevitably experience centrifugal acceleration several times higher than the threshold values of their sensitivity of 0.08 - 0.14 m/s2[1].

2 Methods and materials

2.1 Measuring the distance between otolith organ and the axis of head rotation

For testing the theory of the contribution of otolith organs to the sensitivity of angular accelerations, first of all we need a large database of parameters that are independent of theoretical calculations, such as the distance of the location of the otolith organs from the axis of rotation of the head.

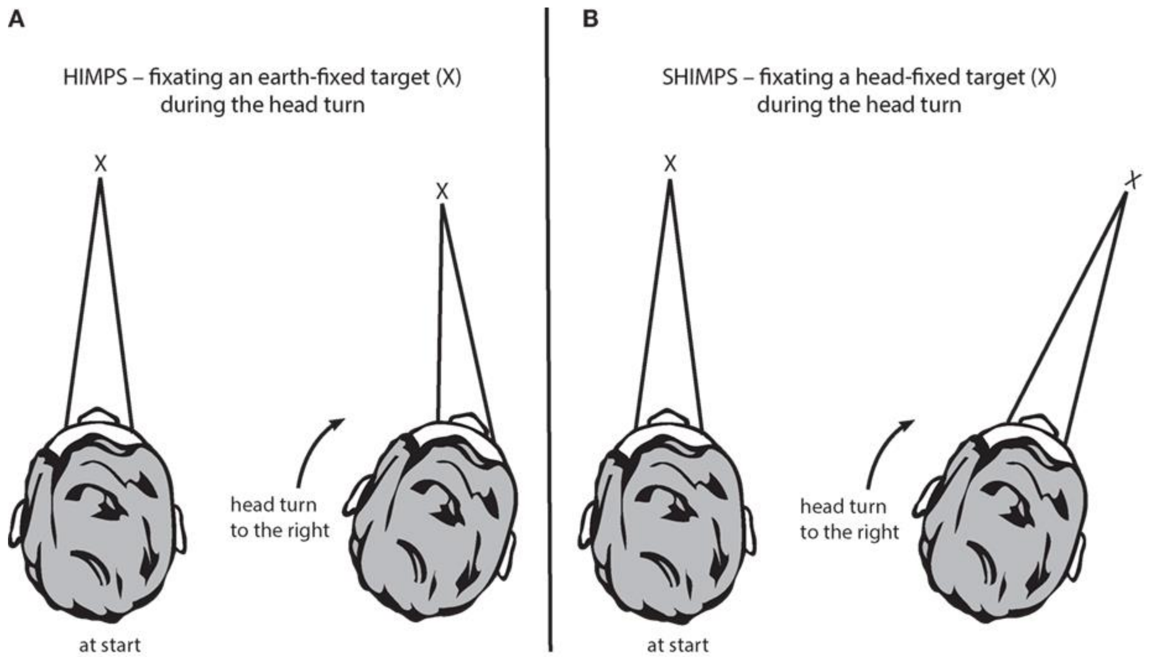


Figure 12 – A- Head Impulse Test, B – Suppressed Head Impulse Test

Spontaneous nystagmus occurs when the eye is in the extreme orbital position, expressed in a slow tilt of the eye to the central axis and, along the next rapid phase of returning to the extreme position. It can manifest itself in both horizontal and vertical directions, and its appearance indicates a malfunction of the stem neural integrator, which is responsible for keeping the gaze.

Research material for measurement was extracted from the Max Plank Institute Leipzig Mind-Brain-Body MRI head dataset[28]. During the resting state scans, participants were instructed to remain awake with their eyes open and fixate on a low-contrast fixation cross on grey background. After the resting state scans, the participants were free to leave their eyes open or closed, or even sleep during the other scans. Dataset of 50 healthy participants comprising by two groups: 1) young group 25.1 +- 3.1 years, range 20-35 years; 2) Elderly group 67.6+- 4.7 years, range 59-77 years.

By using this dataset of MRI images we built a three dimensional model of the vestibular apparatus and the axis of the rotation of the head. The process of creating 3D medical models can be divided into three main stages: the first is obtaining a series of medical images of the area of interest in the Digital Imaging and Communication in Medicine (DICOM) format, the second is the creation of a digital three-dimensional model, and the final is the direct printing of the physical object.

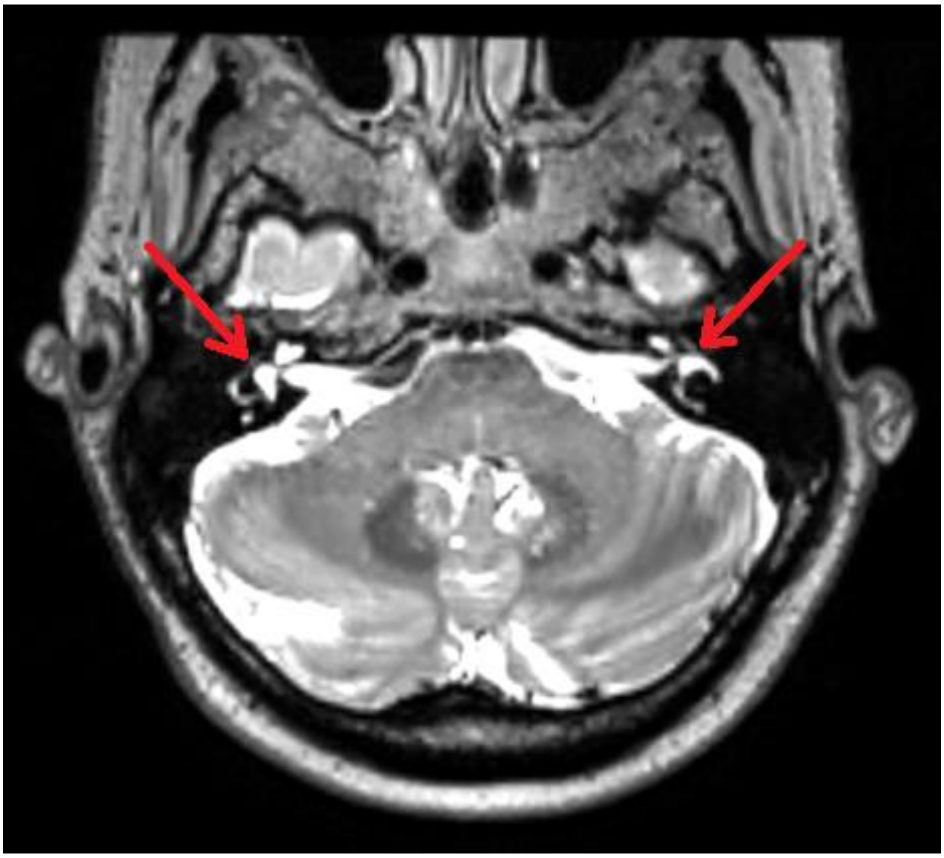


Figure 13 – MRI T2 image of human head. Vestibular organs are indicated by red arrows

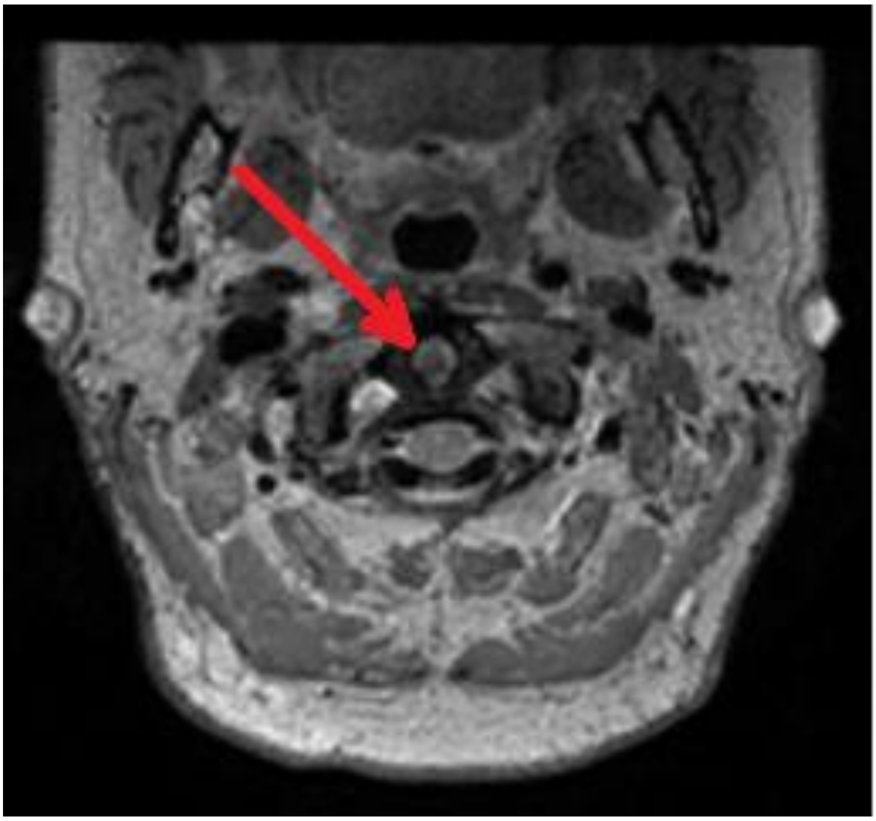


Figure 14 – MRI T2 image of human head. Axis dens (axis of rotation) is indicated by red arrow

For the successful production of 3D models, the obtained DICOM images must have high spatial resolution, good tissue differentiation, and a minimum slice thickness. For high-quality reconstruction of digital 3D models, the slice thickness should not exceed 1 mm. Currently, the sources of DICOM images, on the basis of which digital models for 3D printing can be created, are methods of radiation diagnostics, such as computed and magnetic resonance imaging and computed tomography. For the getting information about distance between otolith organs and the axis of rotation of the head which goes through the second neck bone dens which looks like a tooth I measure it using the MRI images of 12 volunteers from Leipzig Mind-Brain-Body dataset[28].

For the graphical presentation of individual anatomical structures in the form of virtual three-dimensional objects use the technique of volumetric three-dimensional rendering. To do this, the operator defines threshold values for the raster contrast (for example, those that correspond to bone density). After that, a three-dimensional model is built corresponding to the specified range in the 3D Slicer software package[29]. To understand the peculiarities of constructing three-dimensional images, let us consider the algorithm used in the 3D Slicer software package. By changing the methods of graphic processing and image presentation, it is possible to create complex, multi-component models, consisting of separate elements that correspond to bones, muscles, airways, vessels, and the like. Some models are highlighted in different colors and change their transparency to obtain the most visual and easy-to-understand image of the research object.

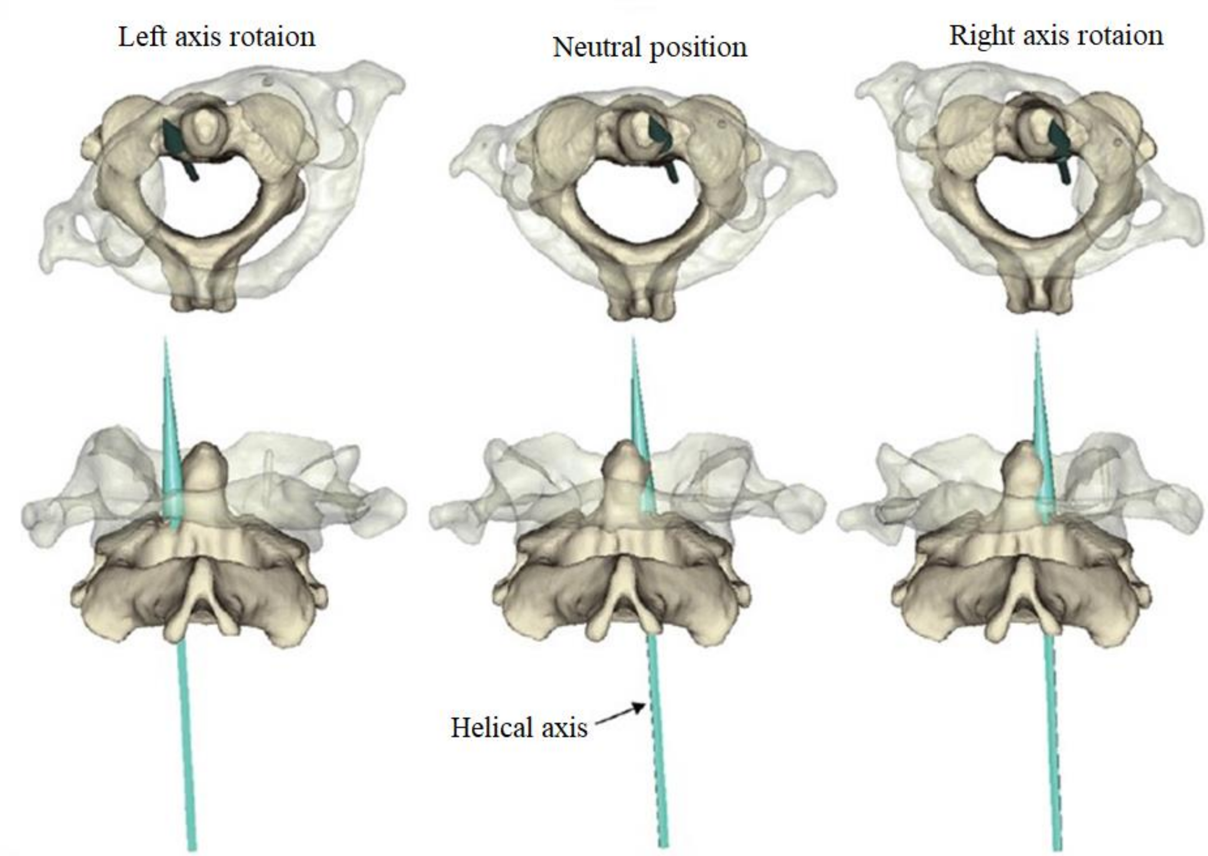


Figure 15 – Atlantoaxial 3D-model and helical axis orientation and location during axial rotation in vivo. Superior view and posterior view for three discrete positions

2.2 Head movement during head impulse test

According to the results of the head impulse test for 10 healthy volunteers, an averaged graph of the head rotation speed during the test was constructed (Figure 16). To process the data obtained during testing, as well as to calculate the magnitude of the centrifugal forces applied to the otolith organs, the Matlab software package was used.

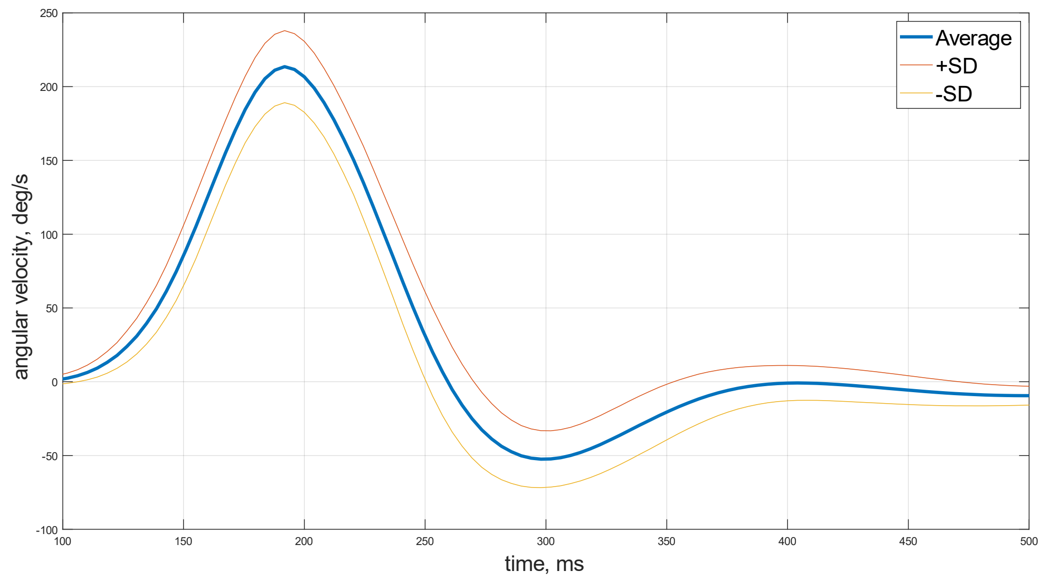


Figure 16 – Averaged head angular velocity during head impulse test: average (blue), standard deviation (SD) (yellow and red)

During the head impulse test when we turn patient`s head at the speeds up to the 300 degrees per second we create not only spin acceleration but the lineal acceleration too. This assumption may allow us to make a mathematical model with which we can calculate the displacements of otolith membrane and the force that it gets. Head impulse test reveals dysfunction of individual vertical semicircular canals in vestibular patients[30]. Unlike search coils, which are currently the only alternative, this new method for detecting dysfunction of individual vertical semicircular canals is fast, non-invasive and practical in the clinic.

2.3 Modeling otolith dynamics

In this study the following dynamics equation has been used [31]:

$$m_+\ddot{x}(t) + B * \dot{x}(t) + k * x(t) = m_- * \omega^2 * R = f(t) \tag{3}$$

Parameter	Value	Units
m_+	$1.413 * 10^{-6}$	kg
m_-	$0.628 * 10^{-6}$	kg
B	$1.643 * 10^{-3}$	kg/s
k	1.309	kg/s^2

m_+ - the mass of the otolith, m_- - mass of the otoconia, B - viscosity coefficient, k – elasticity coefficient, R – distance from the head axis of rotation to the otolith organ, ω – angular head velocity; f(t) – external force applied, centrifugal force.

A typical approach to solving higher-order ordinary differential equations in Matlab is to convert them to systems of first-order differential equations, and then solve those systems. using a change of variables. Let $\mathrm{x(t)} = \mathrm{x}_1$ and $\frac{\mathrm{dx}}{\mathrm{dt}} = \mathrm{x}_2$ such that differentiating both equations we obtain a system of first-order differential equations $\frac{\mathrm{dx}_1}{\mathrm{dt}} = \mathrm{x}_2$ and $\frac{\mathrm{dx}_2}{\mathrm{dt}} = -\frac{\mathrm{kx}_1}{\mathrm{m}_+} - \frac{\mathrm{Bx}_2}{\mathrm{m}_-} + \frac{\mathrm{f(t)m}_-}{\mathrm{m}_+}$. This system was solved in Matlab numerically with the initial conditions: $\mathrm{x(t)} = 0,\ \dot{\mathrm{x}}(\mathrm{t}) = 0$. f(t) was presented either as 1) the centrifugal force, where value of the distance between the otolith organ and axis of rotation $\mathrm{R} = 35\ \mathrm{mm}$, and the average profile of head angular velocity $\mathrm{w(t)}$ as shown in Fig. 16, or 2) by the constant gravity force $\mathrm{f(t)} = \mathrm{m}_-\mathrm{g}$, where $\mathrm{g} = 9.8\ \mathrm{m/s^2}$.

3 Results

3.1 Segmentation of MR-images and measurement the distance between otoliths and axis of head rotation

Figure 17 shows 3D model of a second vertebra and two vestibular systems based on the segmentation of a series of 2D images in program package Slicer 3D.

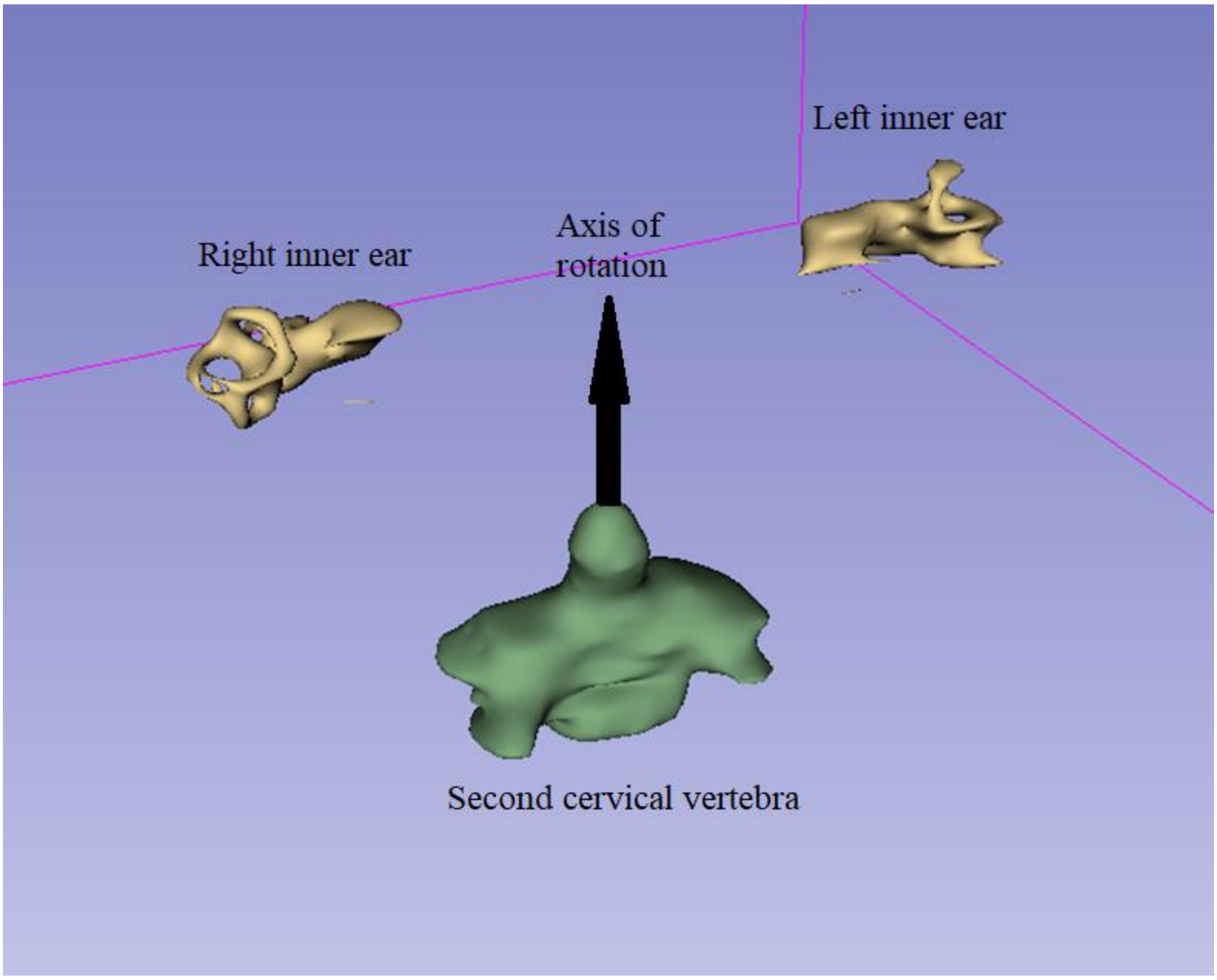


Figure 17 – 3D model of second vertical vertebra (green) and two inner ears (yellow), it helps to recognize the sizes and distance between them

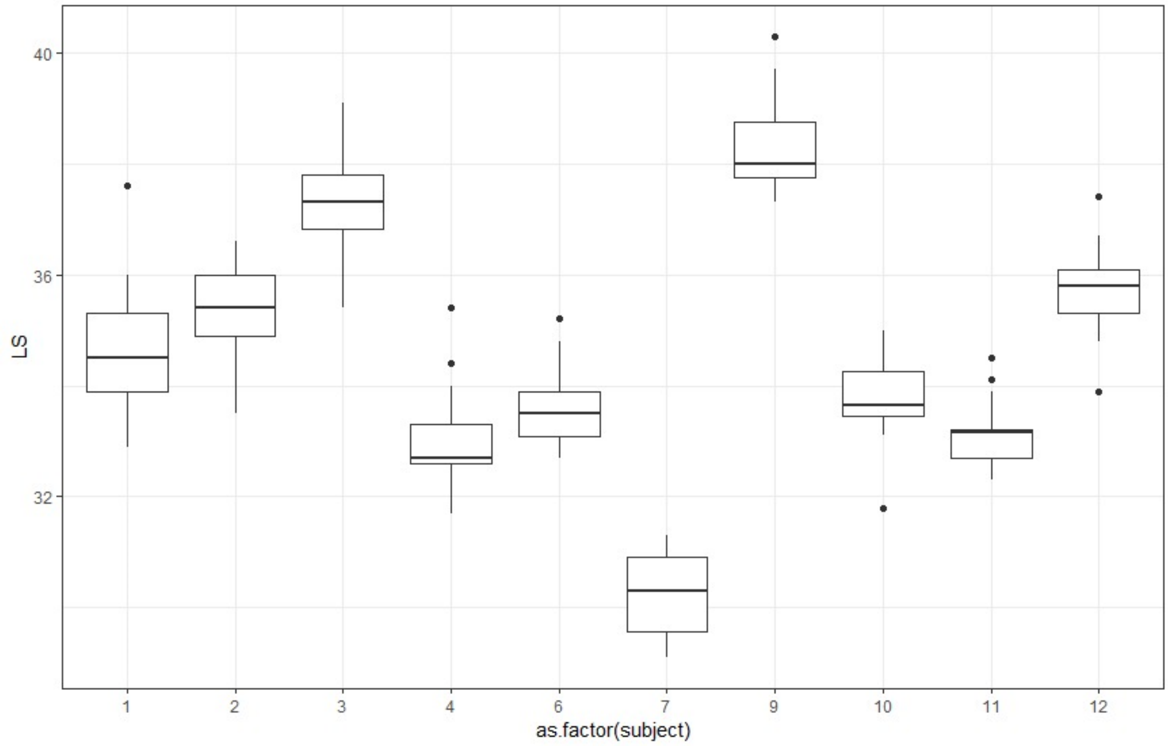


Figure 18 – Distance distribution between axis of rotation and left side otolith organ

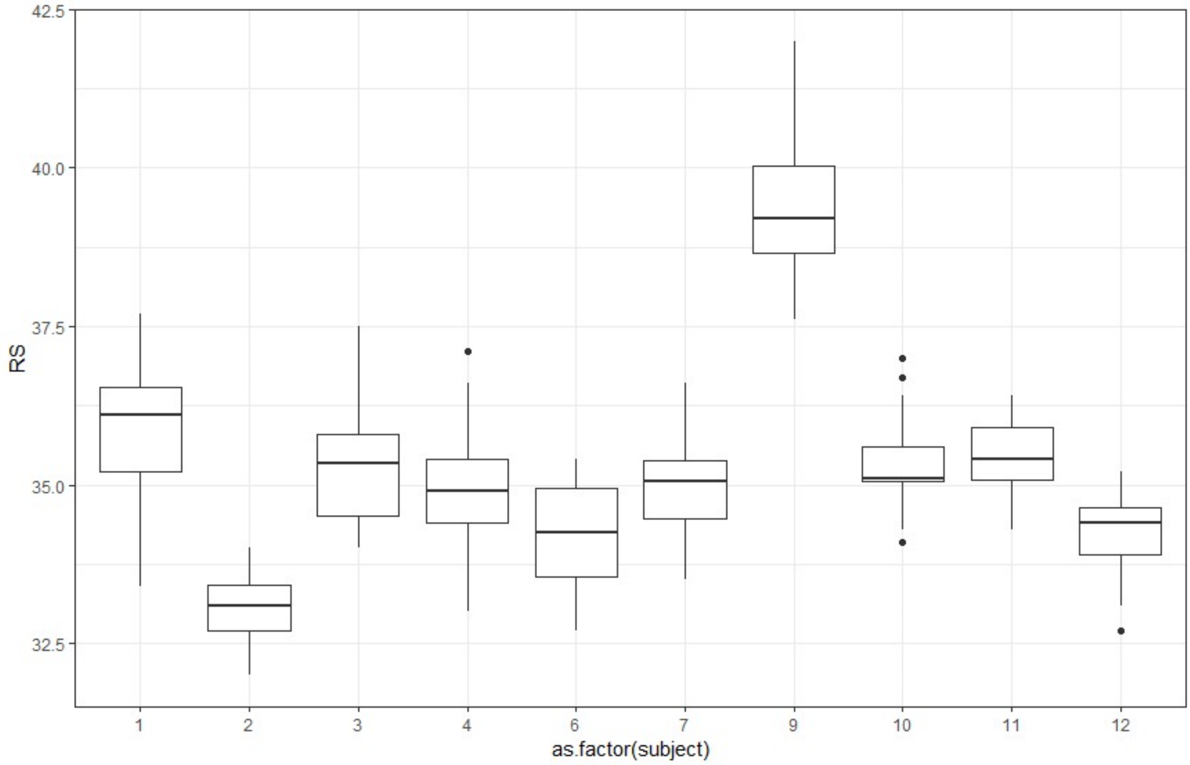


Figure 19 – Distance distribution between axis of rotation and right side otolith organ

As the measuring results you could see a distance distribution between axis of rotation and left (Figure 18) and right otolith organ (Figure 19), these results based on different genders and ages of volunteers so they are pretty scattered but for sure we could say that the mean distance is about 35 mm.

3.2 Otolith dynamics simulation

The numerical solution of the model (2) gives the following results: the values of the otolith membrane displacement were obtained depending on time. During the HIT the highest displacement of the otolith membrane is to 0.2 um (Figure 20).

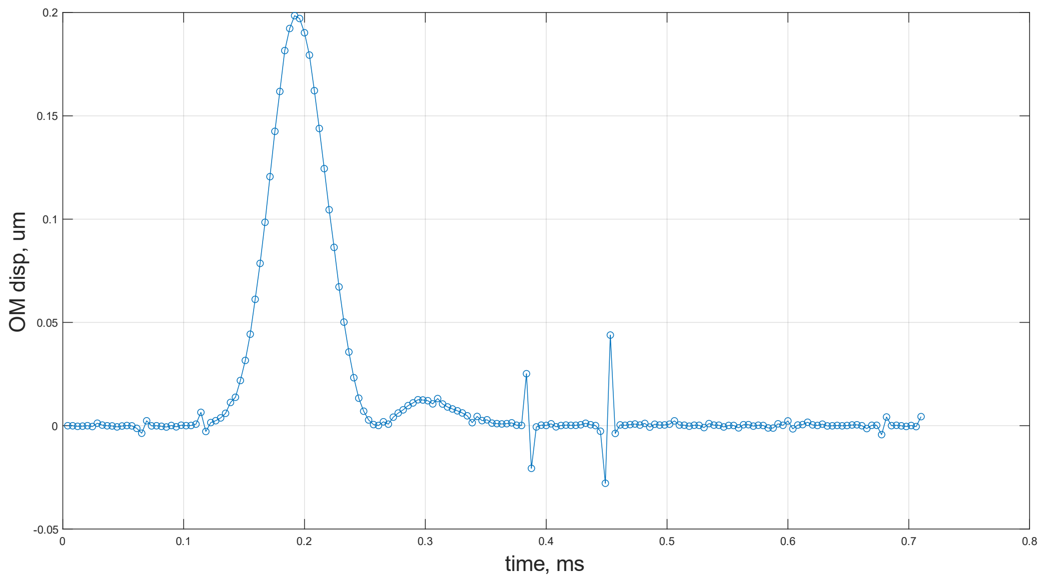


Figure 20 – Displacement of the otolith membrane (OM) during HIT

Gravity acceleration was introduced to right side of the equation to see how otolith membrane will deflect and to check the model. Simulation showed that the highest point displacement is equal to 4 um (Figure 21).

Since linear acceleration can be provided as gravitational field of the Earth, and linear motion, there is a problem of ambiguity of sensory information. In otoliths, as in canals, there is some duplication of function, which consists in the similarity of receptors at both sides. Within each otolith macula, a sinuous zone, the striola, separates the direction of polarization of the hair cells on each side. Consequently, tilting the head increases the afferent signal from one part of the macula, while decreasing firing from another part of the same macula. This the push-pull mechanism of sensory input from each side makes the otoliths less vulnerable in unilateral vestibular lesions compared to semicircular canals. Like canals, otoliths are designed so that they can respond to movement in all three measurements. However, unlike canals, which have one sensory organ per axis of angular motion, otoliths have only two sensory organs for three axes of linear motion[32]. In a person in an upright position, the sacculus is directed vertically (parasagittal), while the utriculus is oriented horizontally (in the same plane as the lateral semicircular canals). The sac (sacculus) perceives linear acceleration in its plane, which includes acceleration oriented along the vertical axis, as well as linear motion along the anteroposterior axis. The uterus (utriculus) records acceleration in its horizontal plane, which includes lateral accelerations along the frontal axis (the assumed line drawn between the external auditory canals), as well as anteroposterior movement[33].

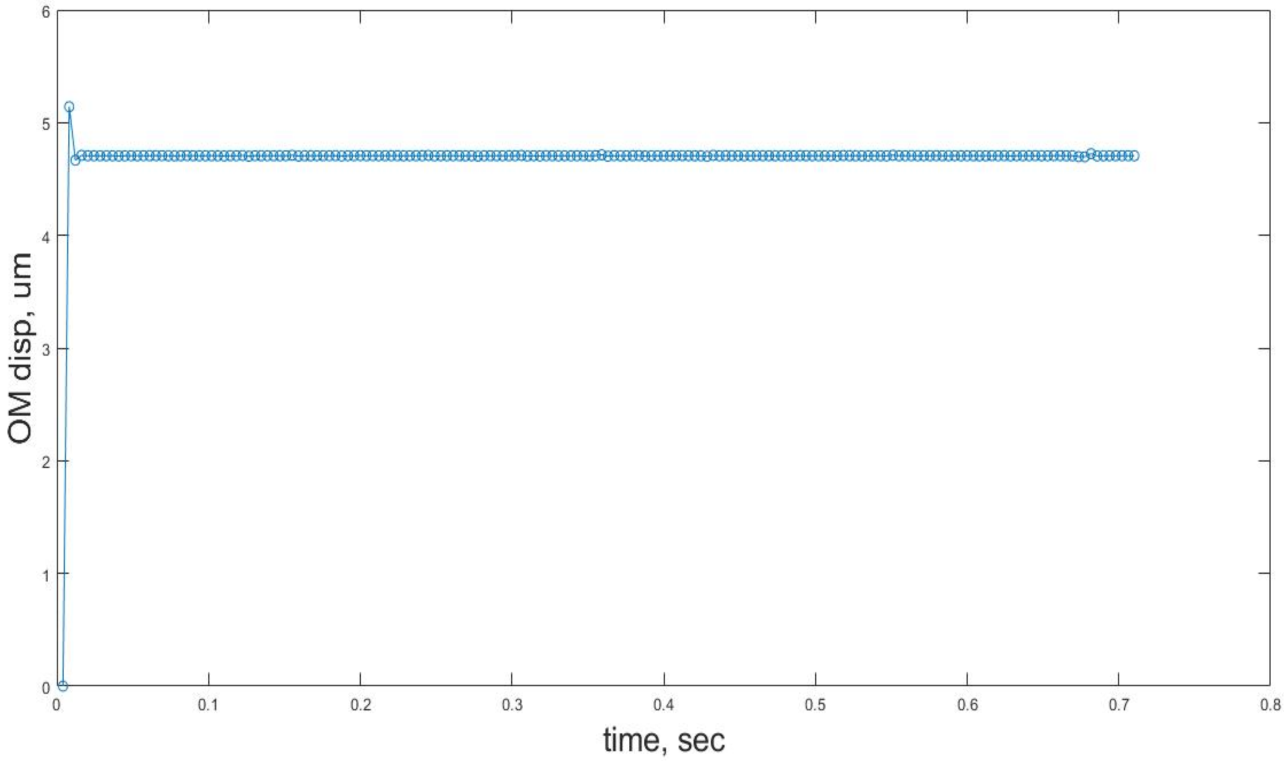


Figure 21 - Displacement of the otolith membrane (OM) by gravity acceleration

The Fourier spectrum of the centrifugal acceleration was calculated using FFT function in Matlab to investigate if the head impulse test trace fits the sensitivity range of the otoliths (Fig. 22). The most dominant frequency in the acceleration profile was 1.4 Hz which is still in the range of theoretical otolith sensitivity.

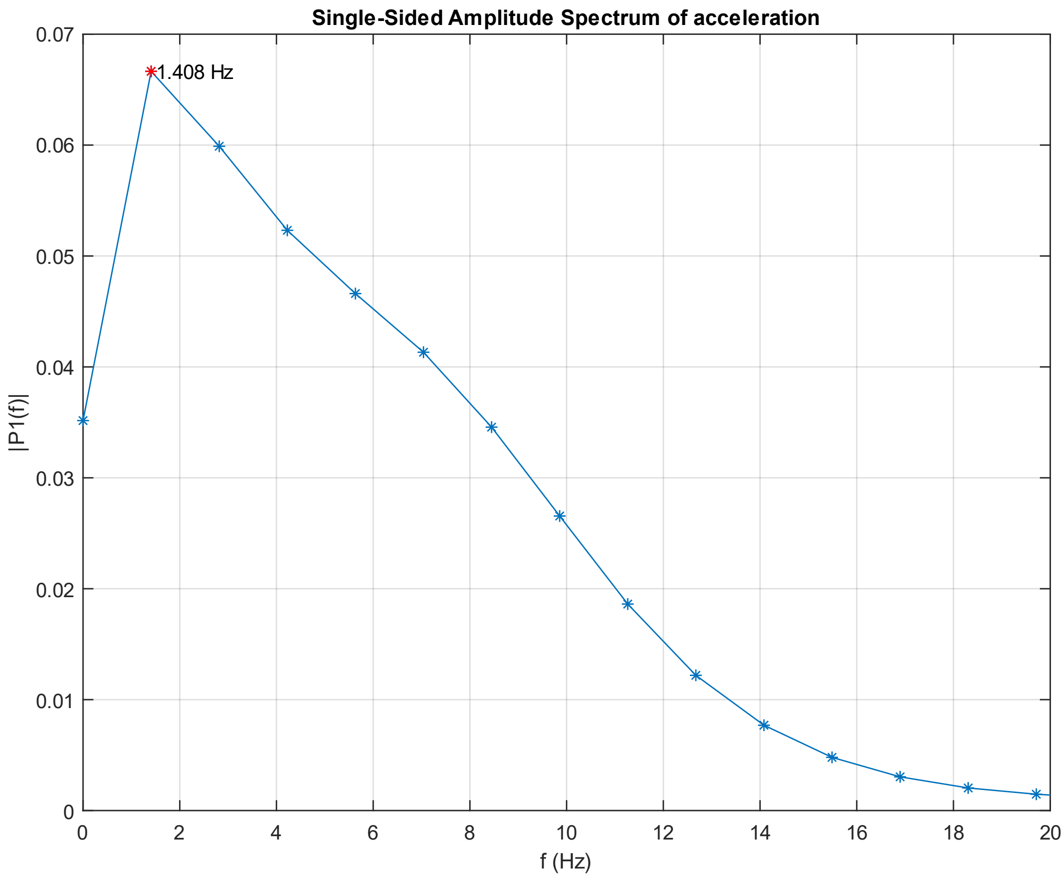


Figure 22 – Fourier spectrum of the average head turn acceleration. Dominant frequency is indicated with red asterisk

4 Discussion

We can see that the results of model calculation are correct in comparing to another article which research was based on first otolith membrane model[34].

The rest of parameters in the model remain a big point of the discussion. The sensitivity analysis is required to identify the key parameters and the degree of their contribution to the model output.

1. A mathematical model of the otolith membrane reaction was obtained. mechanical stimulus corresponding to the real stages of the process transformation of mechanical stimulus, occurring in the secondary mechanoreceptor. Taken together, the results obtained indicate the possible application of the developed mathematical model to analyse functioning of the otolith membrane in various conditions, in particular rotations. Relatively simple form of solution allowed us to show that the displacements of different parts of the OM are different and depend on the configuration of the otolith membrane and orientation relative to the external force. According to the results of the tests and processing the mathematical model it`s clear that the ration between theoretical displacement amplitude during HIT and Earth graviton is equal to 1:25, so the highest simulated otolith displacement

1. Under the action of gravity – $d_g = 4\ um$;

2. During the HIT - $d_{HIT} = 0.2\ um = 5\% * d_g$;

2. The otolith organ sensitivity threshold values is about **0.08 - 0.14 m/s²** when the peak acceleration during HIT is **0.42 m/s²**

3. The frequency at which the otolith amplitude displacement is maximal V_{max} shifts toward low frequencies with the growth of the otolith mass

4. HIT max frequencies 1,4 Hz is comparable with otolith sensitivity

Experimental verification of the model is needed by the outer-counter roll test. The next step is extend the model by Coriolis force and explore its impact on the OM displacement.

CONCLUSION

Simulation of the otolith dynamics showed that the peak acceleration of the otolith membrane during head impulse test in higher than the lower threshold of motion perception. This may indicate that head impulse test consisting of rotations only activates not only the semicircular canals but the otolith organs as well. Further, the sensitivity analysis of the model used is needed to evaluate the key parameters influencing the simulation outcome. On top of that, the simulation results should be verified experimentally for example by means of outer counter roll test.

1) 50 MRI T2 images of healthy volunteers were segmented using 3D-Slicer. The distances between the axis of head rotation (2nd vertebra) and the otolith organs on the left and on the right sides were measured.

2) The average trace of head angular velocity was constructed based on recordings of head movements during the head impulse test in a group of 30 healthy volunteers. Peak angular velocity was identified.

3) Second-order dynamics model of the otolith membrane was modified for modelling the motion of the otolith membrane under action of centrifugal force arising during head impulse test.

4) The displacement of the otolith membrane was simulated under the constant acceleration (gravity) condition and during the head impulse test. The simulation results show that the centrifugal acceleration during head impulse test is higher than the thresholds of motion perception therefore it might be stated that otolith organs are activated during fast rotational head movements.

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Отчет о проверке на заимствования №1

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