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Vestibular Reflexes: Evaluation and Relevance in Microgravity

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ABSTRACT
Maintaining postural equilibrium, sensing movement, and maintaining an awareness of the relative location of our body parts requires the precise integration of several of the body's sensory and response systems including visual, vestibular, somatosensory (touch, pressure, and stretch receptors in our skin, muscles, and joints), and auditory. Vestibular system plays important part in maintaining balance in microgravity environment. Understanding vestibular system and vestibular reflexes will help in training of space crew, detection of vestibular pathologies and prevention & treatment of space motion sickness. This review covers the vestibular reflex pathways, tests to check integrity of these pathways, effect of microgravity on vestibular system and role of vestibular system in space motion sickness
Key words – *vestibular reflexes, space motion sickness.*

Introduction

The vestibular system, which contributes to our balance and our sense of spatial orientation, is the sensory system that provides the dominant input about movement and equilibrioception. Together with the cochlea, a part of the auditory system, it constitutes the labyrinth of the inner ear, situated in the vestibulum in the inner ear. As our movements consist of rotations and translations, the vestibular system comprises two components: the semicircular canal system, which indicate rotational movements; and the otoliths, which indicate linear accelerations. The vestibular system sends signals primarily to the neural structures that control our eye movements, and to the muscles that keep us upright. The projections to the former provide the anatomical basis of the vestibulo-ocular reflex, which is required for clear vision; and the projections to the muscles that control our posture are necessary to keep us upright.

Vestibuloocular reflex (VOR) is only one of 3 vestibular reflexes. The vestibulospinal and vestibulocollic reflexes also contribute to stability. Of the 3 vestibular reflexes, the vestibulocollic reflex is the least understood. The vestibulocollic reflex is indicative of otolithic (saccular) function and can be elicited by direct (intraoperative) stimulation of the inferior vestibular nerve, acoustic stimuli, mechanical stimulation of the forehead, and galvanic stimulation. The response can be measured as a myogenic potential in the ipsilateral sternocleidomastoid and trapezius muscles. The test used, a vestibular evoked myogenic potential (VEMP) test, continues to involve in its clinical application.

Space motion sickness (SMS) is an important medical problem facing any space programme. Proposed etiological factors in the elicitation of space motion sickness are evaluated including fluid shifts, head movements, visual orientation illusions, Coriolis cross-coupling stimulation, and otolith asymmetries Two theories that have been advanced to explain SMS are the "fluid shift theory" and the "vestibulo-ocular sensory conflict theory". The "fluid shift theory" pre-supposes an active or passive shift of body fluid to the central nervous system (CNS) and vestibulo-auditory mechanisms. In contrast, the "sensory conflict theory" hypothesizes that unfamiliar acceleration and gravitational inputs from the middle ear conflict with visual inputs and lead to SMS [1]. We will discuss the relevance of vestibular reflexes in maintaining balance in microgravity and evaluation of the vestibular system in preflight tests

Vestibuloocular reflex (VOR)

The vestibulo-ocular reflex (VOR) or oculovestibular reflex is a reflex eye movement that stabilizes images on the retina during head movement by producing an eye movement in the direction opposite to head movement, thus preserving the image on the center of the visual field. When the head moves, the vestibuloocular reflex responds with an eye movement that is equal in magnitude but opposite in direction. Head movements, rotational and translational, stimulate the vestibuloocular reflex. With a rotational movement, the head moves relative to the body. Examples of this include turning the head back and forth, nodding, and bringing the ear in contact with the shoulder. Translational movements occur when the entire body (including the head) is moved in tandem. Translational movements may occur when an individual stands on a moving sidewalk. Thus, rotational vestibuloocular reflex (r-VOR) responds to angular motion of the head and results from stimulation of the semicircular canals, whereas translational vestibuloocular reflex (t-VOR) responds to linear motion of the head and results from stimulation of the otolithic organs. Separate studies have shown that visual acuity declines by 50% at a point 2° from the center of the fovea.[2,3].

The fovea is that part of the retina where photoreceptor density is greatest and visual acuity is highest. Thus, the main purpose of the vestibuloocular reflex is to maintain objects on the fovea, which thereby allows a person to visualize objects clearly during brief head movements. Since the function of the otolith system depends on the presence of contact forces opposing gravity, it is disabled in weightlessness and may send misleading positional information to the brain. Without the contributions of the otolith system it is difficult in space to distinguish self-motion from object motion. Furthermore, the disintegration of information from the neck position receptors from those of the otolith system can lead to additional illusory positional sensations. Since the function of the semicircular canal system in previous space flights was found to be essentially undisturbed [4].

Evaluation of Vestibuloocular reflex

A simplistic view of the vestibuloocular reflex (VOR) involves a 3-neuron arc that consists of the vestibular ganglion, vestibular nuclei, and oculomotor nuclei (Fig 1). Although this arc provides a basic framework, the pathways involved in the generation of the vestibuloocular reflex are much more complex.

During rotational movements of the head, the endolymphatic fluid within the semicircular canals shifts because of its inertia, which deflects the cupula. Endolymphatic flow toward the ampulla is excitatory in the horizontal canals, while flow away from the ampulla is excitatory in the superior and posterior canals. Afferent nerves from the ampulla carry both excitatory and inhibitory signals to the 4 major vestibular nuclei: medial vestibular nucleus, lateral vestibular nucleus, inferior or descending vestibular nucleus, and superior vestibular nucleus. Different regions within each of the nuclei project to the oculomotor nuclei (cranial nerves III, IV, and VI). Efferent signals from these nuclei then result in contraction and relaxation of the appropriate ocular muscles.

Excitation of the superior canal results in contraction of the ipsilateral superior rectus and contralateral inferior oblique muscles and relaxation of the ipsilateral inferior rectus and contralateral superior oblique muscles, which results in an upward torsional eye movement. Excitation of the posterior canal results in contraction of the ipsilateral superior oblique and contralateral inferior rectus muscles and relaxation of the ipsilateral inferior oblique and contralateral superior rectus muscles. This results in a downward torsional eye movement. Finally, excitation of the lateral canal results in contraction of the ipsilateral medial rectus and contralateral lateral rectus muscles and relaxation of the contralateral medial rectus and ipsilateral lateral rectus muscles. This results in a horizontal eye movement toward the opposite ear.

The vestibulocerebellum compares input from visual and vestibular sensors and mediates changes in the vestibuloocular reflex after vestibular injury or change in visual function. In addition to oculomotor projections, the vestibular nuclei send fibers to the vestibulocerebellum, the nucleus prepositus hypoglossi, and the cells within the paramedian tracts. The nucleus prepositus hypoglossi is crucial for the maintenance of a steady gaze, while the cells within the paramedian tracts are responsible for relaying information to the vestibulocerebellum, specifically the flocculus. Reciprocal projections to and from the cerebellum assist in fine motor control of eye movements. The latency of action of the rotational vestibuloocular reflex (r-VOR) is 7-15 milliseconds, which is the time required for the eyes to respond in an equal, but opposite, manner to the motion of the head. This time is remarkably fast compared with the latency for visually mediated eye movements, which is longer than 75 milliseconds.

Rotational Vestibuloocular Reflex

The rotational vestibuloocular reflex is analyzed for 3 parameters: gain, phase, and symmetry. Gain is the ratio of the amplitude of eye movement to the amplitude of the head movement (stimulus). Phase is a parameter that describes the timing relationship between head movement and the reflexive eye response. When the head and eyes move at exactly the same velocity in opposite directions, they are said to be completely out of phase, or 180°. If the reflex eye movement leads the head movement, a phase lead is present. Likewise, if the compensatory eye movement trails the head movement, a phase lag is present. Finally, testing is analyzed for symmetry. Symmetry is a comparison of the slow component of the nystagmus when the head is rotated to the right compared with rotation to the left. Each of these parameters is useful in the diagnosis and localization of vestibular lesions.

Electronystagmography (ENG) and Videonystag-mograhy (VNG) assess vestibularocular reflex (VOR) using electrodes that detect spontaneous or induced nystagmus, by lateral ocular movement, positional modifications, caloric and rotation tests. It provides information on symmetry of the vestibular lesion that affects the lateral semicircular canal. Isolated, it does not provide any diagnosis, but it is useful to differentiate central from peripheral causes of dizziness. A study of horizontal VOR in space flights was carries out by NASA [5] which challenged the theory that changes in the vestibulo-ocular reflex (VOR) during space flight have been suspected of contributing to space motion sickness. The horizontal VOR was studied in nine subjects on two space shuttle missions. Active unpaced head oscillation at 0.3 Hz was used as the stimulus to examine the gain and phase of the VOR with and without visual input, as well as the visual suppression of the reflex. No statistically significant changes were noted inflight in the gains or phase shifts of the VOR during any test condition, or between space motion sickness susceptible and nonsusceptible populations. Although VOR suppression was unaffected by spaceflight, the space motion sickness-susceptible group tended to exhibit greater error in the suppression than the non susceptible group. Hence it was concluded that at this stimulus frequency, VOR gain is unaffected by spaceflight, and any minor individual changes do not seem to contribute to space motion sickness. Microgravity effect on the vestibulo-ocular reflex is dependent on otolith and vision contributions [6]. Certain non specific changes VOR changes probably resulted from the absent adequate otolith stimulation and reduced otolith influence upon semicircular canal function. The stability of the space pattern of interactions in the readaptation period depended on the time spent in microgravity. Visual-vestibular interactions revealed in VOR evoked by head movements with open eyes, vision dominates when a conflict arises between space and terrestrial patterns of sensory interactions.

Transalational Vestibuloocular Reflex

The translational vestibuloocular reflex (t-VOR) pathways are activated in response to stimulation of the otolithic organs. The utricle responds to lateral translation stimuli, whereas the saccule responds to vertical translations. Translational vestibuloocular reflex pathways have not been studied as extensively as the pathways for the rotational vestibuloocular reflex. However, translational vestibuloocular reflex pathways also appear to be mediated by projections to the ocular motor nuclei via projections from the vestibular nuclei. Specifically, excitation of the utricular macula results in contraction of the ipsilateral superior oblique, superior rectus, and medial rectus muscles and relaxation of the contralateral inferior oblique, inferior rectus, and lateral rectus muscles.

The translational vestibuloocular rotation (t-VOR) and interaction of the otolith-ocular responses are not routinely tested in most laboratories. These tests are mostly considered experimental and often involve sophisticated, expensive equipment such as a linear sled cart, off-vertical axis rotation, or a platform suspended from the ceiling (ie, parallel swing). Newer, less expensive techniques in development include manual translational heaves and a head sled that, unlike the linear sled, moves only the head. Transational heaves have been used by some authors [7] to evaluate otolith function but it is still in nascent stage.

A Single-case, longitudinal studies of the three-dimensional vestibulo-ocular response (VOR) conducted with two spaceflight subjects over a 180-day mission was carried out [8]. The reduced torsional VOR gain was seen which in microgravity was attributed to the absence of the gravity-dependent, dynamic stimulation to the otoliths (primarily utricles). The observed increase in torsional VOR gain from the 1st to the 6th month in microgravity demonstrated the existence of longer-term adaptive processes.

Vestibulospinal Reflex

The vestibulospinal reflexes (VSR) keep the body upright and prevent falls when the body is unexpectedly knocked off balance. The vestibulospinal reflex allows for input from the vestibular organs to be use for posture and stability in a gravity environment.The projections from the vestibular nuclei travel to antigravity muscles for coordinated movements to maintain posture.The vestibulospinal tract is one of the descending spinal tracts of the ventromedial pathway. It originates from the vestibular nuclei of the medulla, which conducts information from the vestibular labyrinth in the inner ear.

Motion of fluid in the vestibular labyrinth activates hair cells that signal the vestibular nuclei via cranial nerve VIII.

A method to record human postural sway employs a computerized commercial or custom-built force platform, dual plates with either three or four load cells Each of these platforms is designed to measure the position of the center point of forces during an upright stance, which is a good estimate of the position of the subject's COG if the body is moving slowly. In Visual Feedback Posturography (VFP) The subjects had to move their center of gravity (COG) marker on a computer screen to chosen targets by leaning their body on the platform, and the accuracy, velocity, and side difference of these movements are measured. Two of the more dramatic responses to orbital flight have been postural disturbances and modified reflex activity in the major weight-bearing muscles. Dynamic postural testing with a moving platform was performed before and after space missions. Balance control performance has been systematically tested before and after the flight using a computerized dynamic posturography system widely employed for evaluation of balance disorders [9]. Postflight measurements revealed significant deviations from the results obtained before flight. The strategy used by the individuals for balance is modified, and their behavior indicates a decrease in awareness of the direction and magnitude of the motion. On landing day, every subject exhibited a substantial decrease in postural stability. Some had clinically abnormal scores, being below the normative population 5th percentile. After flights ranging from 5-13 days, postflight re-adaptation took place in about 8 days and could be modeled as a double-exponential process, with an initial rapid phase lasting about 2.7 hours, and a secondary slower phase lasting about 4 days [9].

Vestibulocolic Reflex

Stabilization of the head is required not only for adequate motor performance, such as maintaining balance while standing or walking, but also for the adequate reception of sensory inputs such as visual and auditory information. The vestibular organs, which consist of three approximately orthogonal semicircular canals (anterior, horizontal, posterior) and two otolith organs (utriculus, sacculus), provide the most important input for the detection of head movement. Activation of afferents from these receptors evokes the vestibulocollic reflex (VCR), which stabilizes head position in space [10]. The purpose of the Vestibular Evoked Myogenic Potential (VEMP) test is to determine if the saccule, one portion of the otoliths, as well the inferior vestibular nerve and central connections, are intact and working normally. Figure 2 illustrates the pathway for the VEMP response, which includes the saccule, the inferior vestibular nerve, the vestibular nucleus, the medial vestibulospinal tract, the accessory nucleus, the 11th nerve, and finally the sternocleidomastoid muscle. Abnormal VEMPs might be caused by abnormalities in any of these structures. VEMP has got potential of providing rapid inflight resting potential of saccule which are ‘unloaded’ in microgravity and stimulated with rostral movement and inhibited with caudal movement.

Space Motion Sickness

Space motion sickness (SMS) is experienced by 50 percent or more of astronauts during the first few days of exposure to the microgravity environment of space. SMS is similar to motion sickness on Earth, with symptoms including loss of appetite, malaise, nausea, vomiting, gastrointestinal disturbances and fatigue. SMS not only disrupts the well-being of crew members, but it also can impair their performance during critical stages of spaceflight.The precise cause of space motion sickness is not fully understood. Some authors believe that SMS is not a unique diagnostic entity but a form of motion sickness which arises when movements are made during exposure to unusual force backgrounds both higher and lower in magnitude than 1 g earth gravity [11]. Theories for Space Motion Sickness

Two major theories advanced to account for SMS are the fluid shift theory and the sensory conflict (also known as the neural mismatch, sensory mismatch, or sensory rearrangement) theory [12]. The fluid shift hypothesis suggests that space motion sickness results from the cranial shifting of body fluids resulting from the loss of hydrostatic pressure gradients in the lower body when entering microgravity. The cranial fluid shifts lead to visible puffiness in the face, and are thought to increase the intracranial pressure, the cerebrospinal-fluid pressure or the inner ear fluid pressures, altering the response properties of the vestibular receptors and inducing space motion sickness. The sensory conflict hypothesis suggests that loss of tilt-related otolith signals upon entry into microgravity causes a conflict between actual and anticipated signals from sense organs subserving spatial orientation. Such sensory conflicts are thought to induce motion sickness in other environments [13]. Both theories have got merits and demerits but sensory conflict theory is generally accepted. Figure 3 shows the integration of sensory inputs by the central nervous system.

The sensory conflict theory postulates that motion sickness occurs when patterns of sensory inputs to the brain are markedly rearranged, at variance with each other, or differ substantially from expectations of the stimulus relationships in a given environment. In microgravity, sensory conflict can occur in several ways. First, there can be conflicting information (i.e., regarding tilt) transmitted by the otoliths and the semicircular canals. Sensory conflict may also exist between the visual and vestibular systems during motion in space; the eyes transmit information to the brain indicating body movement, but no corroborating impulses are received from the otoliths (such as during car sickness). A third type of conflict may exist in space because of differences in perceptual habits and expectations. Thus disorder of the vestibular system induced by microgravity environment is the mainstay of basis of SMS. Knowledge of vestibular reflexes and effect of microgravity on them will lead to better training, rehabilitation and pharmacological application to reduce incidence of SMS.

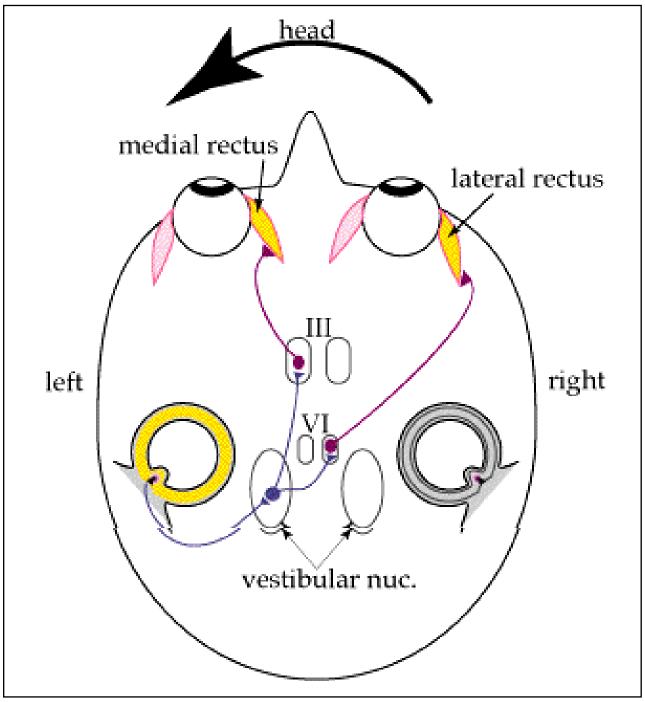

Figure 1 – vestibuloocular reflex

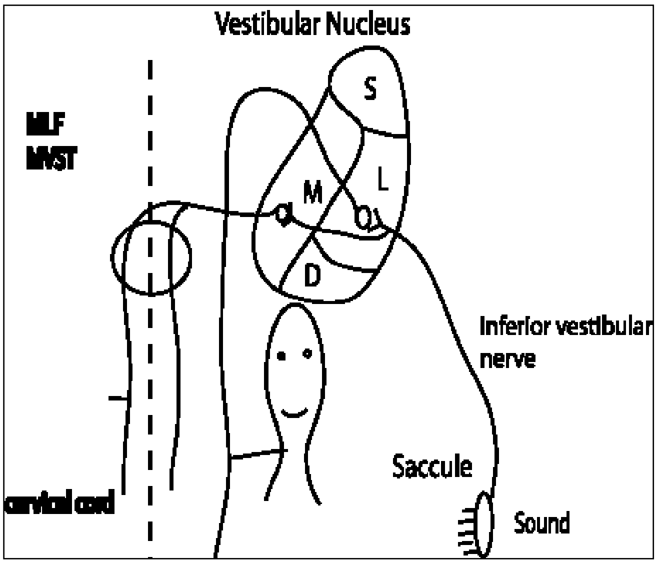

Fig 2 – VEMP pathway

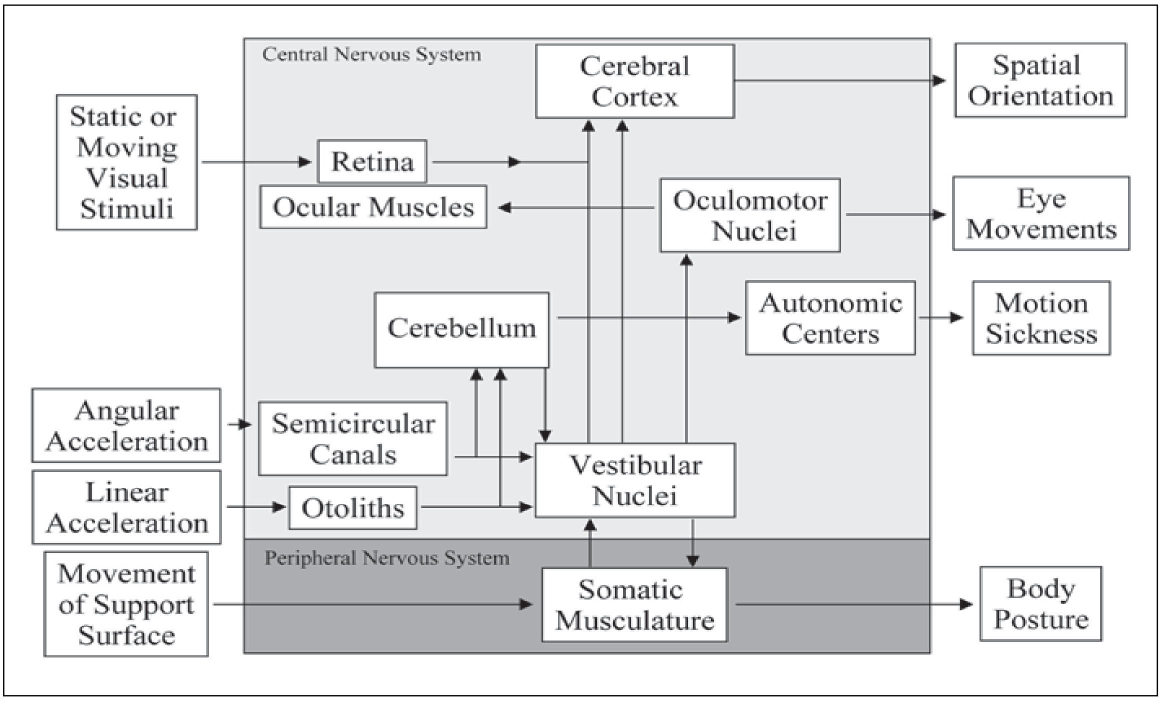

Fig 3 – integration of sensory inputs by CNS

Conclusion

Intact vestibular system is essential for maintaining balance in microgravity environment. In microgravity environment vision dominates the vestibuloocular reflex. Transalational vestibuloocular reflex is predominantly disturbed in less than 1g while rotational vestibuloocular reflex remains unaffected. Vestibular system adapts to microgravity environments within few days and some individuals are more susceptible to others, therefore preflight training in less than 1g environment is essential. Space motion sickness can be explained by sensory conflict theory but this theory has its own caveats and further research is required to explain the lack of predictive power of developing SMS, exact pathway, adaptation and pharmacological therapy.

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