REVIEW ARTILCE

Effect of Vestibular Stimulation on Different Body Systems: A Overview

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ABSTRACT

During development, the vestibular system is fully functional before any other sensory system. Apart from its basic function, vestibular system contributes to a wide range of functions from the level of reflexes to the level of cognition and coordination. Hence, the vestibular system was considered as a sixth sense. As vestibular system relates the body with the gravity, its impact can be observed in all the systems of the body. The present review article explains the complex connections of the vestibular system with different cortical and subcortical structures in controlling the functions of different body functions to establish the homeostasis.

KEY WORDS: Vestibular system, sixth sense, homeostasis.

Introduction

During development, vestibular system is fully functional before any other sensory system. The otolith organs which transduces linear acceleration is the most primitive part of the vestibular system.[1] The anatomy of bony labyrinth was explained in 1610 by Casserii. Further details about the vestibular system were provided by Scarpa in 1789. Histology of the vestibular system was explained in 1800s. Functional aspects of vestibular system were described by Goldberg, Fernandez, and Lysakowski.[2] Vestibular system comprises semicircular canals and otolith organs and information from the vestibular system immediately becomes multisensory and multimodal in the central nervous system.[3] Optimal stimulation of vestibular system is essential throughout the life for maintenance of homeostasis.[4] Vestibular system consists of peripheral sensory apparatus, central processor, and an output mechanism. The motion sensors (hair cells) of the peripheral sensory apparatus send the information to the central processing system (vestibular nuclear complex [VNC] and cerebellum). The central processing system processes the information from the motion sensors and combines the information with other sensory signals to quantify head and body orientation. The output mechanism comprises three reflexes that are vestibuleocular reflex, vestibulocolic reflex, and vestibulospinal reflex.

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The peripheral sensory apparatus

The peripheral sensory apparatus consists of bony, membranous labyrinths, and hair cells. The peripheral vestibular system is located within the inner ear. Three semicircular canals (lateral, superior, and posterior), cochlea and vestibule, constitute the bony labyrinth.[5] The membranous labyrinth is suspended within the bony labyrinth and consists of a membranous portion of three semicircular canals and two otolith organs (utricle and saccule). The utricle senses linear acceleration and position of the head in relation to the gravity whereas the semicircular canals sense the angular acceleration. The bony labyrinth is filled with a fluid called perilymph, and membranous labyrinth is filled with endolymph. The dilated portions of each semicircular canal are called ampulla in which specialized hair cells are located. Hair cells of semicircular canals and otolith organs are motion sensors and convert the movements into neural signals. The afferent neurons that innervate the hair cells are located in the vestibular (Scarpa's) ganglion. The firing rate of the hair cells changes

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depending on the movement of the hairs toward or away from the longest process. The peripheral vestibular system is supplied by the labyrinthine artery.[3]

The central processing system

The central processing system consists of VNC and the cerebellum. The VNC which comprises the superior, lateral, medial, and inferior and the nearby cell groups include the nucleus prepositushypoglossi, cell Group Y and cell Group E integrates information from sensory, motor, and higher level cognitive systems.[4]

The motor output of vestibular system

The output system consists of vestibulo-ocular, vestibulospinal, and vestibulocolic reflexes. Vestibulo-ocular reflex ensures stable vision during movement of the head.[6] The vestibulospinal reflex plays a key role in the maintenance of posture and stabilizes the body and keeps the body upright. Vestibulo-sympathetic reflex (VSR) controls trunk and limb muscles and prevents fall during a change in the posture.[7] The vestibulocolic reflex stabilizes head in space during body movements and decrease unwanted oscillations of the head. Vestibulo colic reflex mainly acts on neck muscles.[8] The VSR that influences blood pressure, heart rate, respiration, and digestion originates from the medial vestibular nucleus and the spinal vestibular nucleus.[9] The vestibulo-thalamo-cortical reflex is essential for maintenance of posture, oculomotor control, spatial and bodily perception, and cognitive functions.[10]

Materials and Methods

The published literature from http://www. google.com, http://www.pubmed.com, British medical http://www.journal.com, Medline, ERIC, http://www. frontiersin.org, and other online journals were performed and analyzed.

Effect of vestibular stimulation on different systems of the body

Vestibular system influences almost all body systems through its projections to different areas of the cerebral cortex, cerebellum, and spinal cord, and other brain structures.[11]

Vestibular interactions with central nervous system

Vestibular stimulation causes vasodilation of cerebral blood vessels through two pathways. First pathway starts with projections from vestibular nuclei to fastigial nucleus, rostral ventrolateral medulla then by vasodilator fibers to cerebral blood vessels. Second pathway starts the projections from vestibular nuclei to nucleus tractus solitarius (NTS), pterygopalatine ganglion, and cerebral blood vessels. Vestibular system has extensive connections with structures of the brain. Stimulation of vestibular nerve evoked potentials in the cortical areas which indicate the presence of vestibular receiving areas in the cortex.[12] The primary area of projection of vestibular nerve in the cortex is located in the superior temporal region.[13] Powerful thalamic activation was observed followed by vestibular stimulation.[14] Vestibular projections from superior and medial vestibular nucleus were identified in the centromedian nucleus, ventral posteromedial, venteral posterolateral, ventral posteroinferior, and ventrobasal thalamic nucleus. Stimulation of thalamic nucleus inhibits pain pathway and relieves pain.[10] Stimulation of vestibular nerve increases neuronal activity in cortex, thalamus, and midbrain.[15] Vestibular system connected with dorsal raphe nucleus leads to the increased release of serotonin. Interestingly, vestibular stimulation causes stimulation and inhibition of hypothalamus.[16] Bilateral projections are present between vestibular nuclei and cerebellum and vestibular stimulation evoke response from purkinje cells.[17]

Vestibular system is also connected with parabrachial nucleus complex, NTS, and dorsal motor nucleus of vagus nerve.[18] Vestibular system is functionally associated with somatosensory systems as vestibular stimulation increases the sensitivity to tactile input and decreases the sensitivity of nociceptive input.[19] Interestingly, vestibular stimulation deactivates visual cortex and decreases attention, while activating sensory cortex.[20] This decrease in attention may have a role in vestibular mediated pain relief.[21] Better pain-relieving effect was observed in face and arms than legs.[21,22] Vestibular system is well connected to limbic system, insula, the cingulate gyrus, the hippocampus, and the parabrachial nucleus, through cerebellar, brainstem, diencephalic centers, and amygdale cells, which are involved in regulation of emotions.[23] Vestibular system is connected to basal ganglia, and electrical stimulation of vestibular system elicits potentials in striatum.[24] Medial and lateral vestibular nuclei send descending projections to spinal cord, which are essential for the maintenance of posture and equilibrium.[25]

Vestibular interactions with endocrine system

Vestibular stimulation modulates secretion of hormones through its connections with different brain structures.

Vestibular modulation of pituitary hormones

Vestibular stimulation modulates secretion of somatostatin which inhibits secretion of growth hormone (GH) through vagal nerve. The response to vestibular stimulation is species specific and varies accordingly. Vestibular stimulation increases secretion of GH and prolactin through increasing secretion of serotonin from dorsal raphe nucleus.[26] Whereas the increase in secretion of gamma-aminobutyric acid (GABA) as a result of vestibular stimulation causes an increase in secretion of GH and luteinizing hormone (LH).[27] Vestibular stimulation causes an increase in leptin secretion which modulates the secretion of LH, follicle-stimulating hormone, and adrenocorticotropic hormone.[28] Supraoptic and paraventricular nucleus respond to vestibular stimulation. The response may be excitation or inhibition depending on the intensity of the stimulation.

Vestibular modulation of thyroid hormones

Vestibular stimulation modulates thyroid hormones through its projections to paraventricular nucleus where the neurons that secrete thyrotropin-secreting hormone (TRH) are located. Vestibular stimulation increases release of leptin through vagal stimulation and leptin stimulates secretion of TRH. It also modulates thyroid secretion through the dorsal raphe nucleus.[29-31]

Vestibular modulation of adrenal hormones

Vestibular stimulation inhibits hypothalamic-pituitary-adrenal (HPA) axis directly through its connections with hypothalamus and indirectly through stimulating hippocampal formation and increasing secretion of GABA from substansianigra.[32-34] Vestibular stimulation modulates aldosterone secretion through the hypothalamus and vagal stimulation.[35] Studies have shown that vestibular stimulation modulates sympathetic nerve activity through diencephalon. Sympathetic nerve activity reduced following vestibular stimulation. However, the response depends on the intensity of stimulation.[36,37]

Vestibular modulation of pancreatic hormones

Vestibular stimulation modulates secretion of pancreatic hormones in humans through its connections with NTS and dorsal motor nucleus of the vagus nerve (DMV). However, the response varies from species to species.[38]

Vestibular modulation of melatonin secretion

Vestibular stimulation modulates secretion of melatonin through its connections with an intergeniculate leaflet, dorsal raphe nucleus, and hypothalamus. Vestibular stimulation modulates melatonin secretion through direct and indirect pathways. Direct projections from vestibular nuclei regulate the circadian rhythm.[39-41]

Vestibular interactions with reproductive system

Changes in the hormonal levels during a menstrual cycle, pregnancy, and menopause interfere with fluids of the vestibular system and may lead to symptoms such as vertigo, dizziness, tinnitus, and nausea. These are the most commonly noted vestibular symptoms in pregnancy.[42] Increase in the estrogen, progesterone, and aldosterone levels in the luteal phase of the menstrual cycle causes physical changes in the vestibular system like modulation of endolymphatic pressure.[43] Vestibular stimulation may prevent stress-induced inhibition on estrogen, progesterone and LH, and testosterone.[44] Vestibular stimulation decreases cortisol levels and prevents suppression of testicular and ovarian functions.[45] Animal studies shown that vestibular stimulation facilitates sexual behavior and efficiency through improving balance and gait in both male and females.[46]

Vestibular stimulation and autonomic modulation of cardiovascular system

Normally functioning vestibular system is essential for maintenance of blood pressure.[47] Damage of vestibular system results in an inability to regulate regional blood flow changes and result in a decrease in blood pressure.[48] Autonomic dysfunction was commonly observed in patients with vestibular abnormalities.[49] It was noted that structural and functional interactions exist between vestibular and autonomic nuclei.[37] Electrical, caloric, rotational, and natural vestibular stimulation regulates blood pressure by reducing sympathetic activity.[50] VSR regulates the distribution of the blood in the body. Stimulation of VSR during movements leads to pooling of the blood in the peripheral areas and decreases venous return. At the same time, vestibular stimulation causes vasoconstriction of arteries through activation of sympathetic vasoconstrictor nerves.[51,52] The response of sympathetic nerves for vestibular stimulation may be excitatory or inhibitory or combination of both. Neural connections are located between medial and inferior vestibular nuclei to nucleus of solitary tract which causes sympathetic inhibition through rostral ventrolateral medulla.[53] Direct projections are present from vestibular nuclei to rostral ventrolateral medulla, which are essential for sympathetic function.[54] Vestibular stimulation increases GABA release from substansianigra which inhibits locus coeruleus (LC) noradrenergic neurons.[55] Otolith system of vestibular apparatus was reported to play a major role in VSR and defects in otolith system leads to orthostatic intolerance.[56] Direct vestibular projections are presented to DMV nerve. Vestibular stimulation stimulates the ipsilateral vagus nerve and increases conduction of vagal afferent signals to the central nervous system.[57] Vestibular stimulation also influences autonomic functions through the parabrachial nucleus.[58] Significant decrease in the heart rate was observed followed by rocking movements.[59] Vestibular stimulation leads to a complex pattern of cardiovascular changes which are different from stimulation of other somatic systems. A study conducted in children with Down's syndrome with congenital heart defects and reported a decrease in heart rate but was within the limits, stating the physiological response of the children to the stimulation.[60] The animal studies reported a decrease in blood pressure by reducing the sympathetic activity as an effect of vestibular stimulations. The effect of a decrease in blood pressure after vestibular stimulation is determined by two factors, namely vagus nerve that controls the decrease in heart rate and the other is the vaso-regulating center, controls the decrease in heart tone.[37]

Vestibular interactions with respiratory system

Vestibular system has an influence on respiratory muscles that ensure steady respiration. Activities of respiratory muscles were attenuated by movement or postural changes. Further, movement can also stimulate pulmonary receptors, stretch receptors, and influence respiration.[50] Vestibular stimulation modulates the activity of inspiratory, expiratory, and upper airway muscles.[61,62] Rotatory vestibular stimulation was reported to increase respiratory frequency in healthy participants but not in patients with vestibular disorders.[63] Increase in respiratory frequency was observed followed by rocking movements, which is independent of frequency and amplitude of the stimulation.[59] Stimulation of vestibular system in preterm infants resets respiratory pattern generator and increases the rate of respiration.[64] Vestibulospinal neurons are reported to play a major role in vestibule-respiratory responses.[65] Recent research reported that stimulation of semicircular canals increases the rate of respiration whereas stimulation of otolith organs reduces the pulse rate. These changes in respiration and pulse rate were the result of vestibule-respiratory reflex.[18,66]

Vestibular interactions with gastrointestinal system

Vestibular system sends projections to parabrachial and adjacent Kölliker-Fuse nuclei which play a key role in generating symptoms of motion sickness.[67] Vestibular projections to dorsal vagal complex modulate motility of stomach and intestine and gastric secretions, which may be dependent or independent of the vagal nerve.[68] Increase and decrease in the intragastric pressure were observed followed by vestibular stimulation.[69] Vestibular projections were observedin dorsolateral portion of the reticular formation of the medulla. Stimulation of areas of dorsolateral portion of the reticular formation of the medulla evokes vomiting like behavior.[70] Increase in the relaxation time of lower esophageal sphincter (LES) and decrease in the duration and amplitude of LES were observed followed by caloric vestibular stimulation in healthy participants. Vestibular stimulation modulates secretion of somatostatin, gastrin, cholecystokinin, and gastrin-releasing peptide through the vagus nerve.[71]

Vestibular interactions with body mass composition

Any form of vestibular stimulation that stimulates otolith organs reduces body fat through vestibulo-hypothalamic pathway.[72] Vestibular stimulation decreases the set-point for body fat through its connections with melanocortin system. Vestibular stimulation activates arcuate nucleus which is a key nucleus in melanocortin system.[73] Vestibular system sends projections to pro-opiomelanocortin in nucleus of solitary tract.[74] Vestibular stimulation modulates signaling of melanocortin system through enzymes which are expressed within vestibular nuclei.[75] Vestibular stimulation may regulate food intake through vagal stimulation, increasing insulin secretion, arcuate nucleus stimulation, and modulation of thyroid hormone secretion. Caloric vestibular stimulation was reported to modulate body perception in healthy individuals.[76]

Vestibular interactions with muscular system

Vestibular system maintains postural balance and equilibrium and is essential for the development of motor development and coordination and helps to improve accuracy of the voluntary movements. Vestibular stimulation mainly causes excitation of extensor or antigravity muscles and reciprocally inhibits flexor muscles.[77] Medial gastrocnemius muscle responds maximum to vestibular stimulation.[78] Vestibulospinal, vestibulecolic, and vestibulo-ocular pathway plays a major in the maintenance of muscle tone. Vestibular stimulation by spinning, sliding, bouncing up and down improved motor functions, and pinch strength in children with cerebral palsy.[78,79] Exercises stimulating vestibular system was reported to be beneficial for the elderly population and individuals with visual impairments.[80] Noisy-galvanic vestibular stimulation was reported to improve motor performance in Parkinson's patients. Vestibular stimulation increased the amplitude of the negative slope of motion-related cortical potential in the brain areas for dominant and non-dominant hand function.[81] Gravity changes are induced in muscle and bone through the vestibular system.[82] Vestibular stimulation modulates muscle mass through its connections with the sympathetic system.[83]

Vestibular interactions with kidney

Vestibular stimulation regulates tone of renal blood vessels through modulation of the activity of renal sympathetic nerves,[84] which plays a major role in maintenance of fluid balance.[85,86] Stimulation of renal sympathetic nerve caused sodium and water retention.[87] The vestibular system regulates distribution of blood through sympathetic system and maintains arterial blood pressure.[88] Effect of vestibular stimulation on sympathetic nerves is system specific.[89] Low-intensity vestibular stimulation, induced strong inhibition followed by excitation and high-intensity stimulation, induced inhibition preceded by short-term excitation in renal sympathetic nerve.[90] Neuroanatomical studies confirmed the presence of melanocortinergic projections from medial vestibular nuclei to the renal system.[91] Drugs which are toxic to kidney are reported as ototoxic as the stria vascularis has structural and functional similarities with renal tubules and glomerulus. Vestibular dysfunction was reported in patients with chronic kidney diseases and undergoing dialysis or transplantation.[92]

Vestibular interactions with immune system

Normal functioning of hippocampus is essential for intact immunity. Significant decrease in the IgG and IgM levels was observed followed by dorsolateral hippocampus and ventral hippocampal formation lesions.[93] Normal vestibular functioning is essential for normal functioning of hippocampus.[94] Vestibular stimulation activates hippocampal formation, retrosplenial cortex, and the subiculum.[95] Molecules that are involved in immune signaling (interleukin-1β, −2, and −3) were localized in hippocampal formation, and the levels of these molecules alter during immune challenges.[96] Vestibular stimulation inhibits the stress axis and prevents stress-induced changes in a number of immune cells and dysregulation of cytokines.[97]

Vestibular stimulation and sleep

Use of a cradle is a known method to induce sleep in children throughout the world. Several studies reported that vestibular stimulation induces prolonged and relaxed sleep.[98] In contrast, other studies reported that vestibular stimulation induces wakefulness.[99] Vestibular stimulation may cause both sleep and arousal depending on speed of stimulation.[100] High-speed vestibular stimulation induces wakefulness and low-speed induces sleep, respectively.[101] Recent research reported that natural vestibular stimulation decreases sleep latency and speed up the transition from wakefulness to sleep.[102] Increase in the rapid eye movement sleep was reported followed by vestibular stimulation.[103] Vestibular stimulation influences the sleep-wake cycle through its projections to hypocretin neurons, thalamus.[100,102] Vestibular stimulation not only influences sleep but also changes the pattern of dreams as reported in research that participants experienced dreams with sexual nature followed by vestibular stimulation.[104,105] Vestibular stimulation was reported to induce lucid dreams which is used in the treatment of psychiatric disorders like depression.[106]

Vestibular stimulation and cognition

Vestibular stimulation influences the cognitive functions such as perception of self-motion, bodily self-consciousness, spatial navigation, spatial learning, and memory and object recognition memory.[24] Four pathways through which vestibular stimulation influences the cognition are identified.[107] Parieto-insular vestibular cortex, temporoparietal junction, anterior, posterior parietal cortex, medial superior temporal cortex, cingulate gyrus, and retrosplenial cortex, hippocampal and parahippocampal cortex are the areas of the cortex activated followed by vestibular stimulation. These cortical areas play a major role in spatial cognition.[108] Vestibular lesions may have a negative impact on cognition as it was observed that hippocampus undergoes atrophy followed by lesions of the vestibular system.[108] Vestibular stimulation decreases acetylcholinesterase level and modulates synaptic plasticity of hippocampus and facilitates long-term potentiation.[109] It also induces changes in parietal cortex through direct connections.[110] Vestibular lesions were leaned to cause defects in cognitive functions especially spatial memory defects. It was reported that caloric vestibular stimulation modulates purchase decision-making and decreases the chance of purchasing a product.[111] Galvanic vestibular stimulation induces changes in electroencephalography pattern and improvement in visual memory recall was observed followed by vestibular stimulation.[112] Unilateral caloric vestibular stimulation was reported to improve spatial and verbal memory through activation of the contralateral structures of brain related to cognitive functions.[113] Repeated stimulation of vestibular nerve prevented cognitive decline induced by intracerebroventricular streptozotocin.[114]

Vestibular stimulation and stress

Different forms of rocking had been used across the world to soothe the infants.[115] The soothing effects produced by rocking are through brain stem inhibitory mechanisms. Vestibular stimulation directly inhibits HPA axis through its projections to hypothalamus. Optimal vestibular stimulation directly inhibits HPA axis and decreases cortisol levels within normal limits.[116] Vestibular stimulation inhibits HPA axis indirectly through increasing the secretion of GABA and activation of hippocampal formation. Vestibular stimulation increases secretion of GABA from substantia nigra, and this further inhibits HPA axis.[117] Functional magnetic resonance imaging studies in healthy individuals revealed that vestibular stimulation activates hippocampal formation, subiculum, and retrosplenial cortex.[95] Hippocampal stimulation inhibits HPA axis and decreases corticosteroid levels.[118] Vestibular stimulation increases vagal activity and decreases sympathetic activity.[119] Vestibular stimulation was reported to reduce blood pressure through decreasing sympathetic activity. Vestibular stimulation inhibits LC noradrenergic neurons through GABA ergic and cholinergic pathways.[120,121] In a study, vestibular stimulation showed a decrease in salivary amylase levels, but the effect was not statistically significant.[122]

Vestibular stimulation in clinical practice

Hanging beds were used to stimulate vestibular system by ancient Greek physicians to reduce pain and to induce sleep. Roman physicians used vestibular stimulation to treat mental illness. Researchers have also used conventional swings, rotating chairs to treat various pathological conditions.[123,124] Vestibular stimulation has been suggested as a cure for many clinical disorders, including sleep, mood disorders, chronic pain, Schizophrenia, neuronal development, and neurodegenerative disorders.[125] Caloric vestibular stimulation was reported to modulate cerebral blood flow and used for management of episodic migraine.[126] Noisy galvanic vestibular stimulation was reported to improve gait pattern in patients with vestibulopathy.[127] Vestibular stimulation was reported to be beneficial in the management of conversion disorder,[128] mania,[129] psychosis,[130] mood disorders, attention deficit and hyperactivity,[131] pain, somatoparaphrenia,[132] premenstrual syndrome,[133] obesity,[71] Parkinson's disease, schizophrenia,[134] cerebral palsy,[135] autism,[136] and stress and sleep disorders.[105] In the Indian tradition, swing was a part of the festival celebrations. For example, during the harvesting festival in India such as bisakhi, bihu, and sankranti, and females of all age groups come together and enjoy the swing arranged especially for the occasion. In the present scenario, the traditional Indian culture is replaced by modern lifestyle which increased mental and physical stress. Slowly there has been an increased awareness on the importance of being physically and mentally healthy with remedies such as yoga, meditation, vestibular stimulation, as the simple and easy methods of stress busters to relieve the stress, and its complications. Adapting vestibular stimulation in everyday life, as a regular practice may become an effective tool to reduce the stress and to prevent or delay stress-related disorders.

Conclusion

In summary, the current review explains the complex connections of the vestibular system with different cortical and subcortical structures in controlling the functions of different body functions to establish the homeostasis. It is the need of time to start more translational research in this area to explore the potential benefits of vestibular stimulation.

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