Review Article

Vestibulo-ocular Reflex – A Narrative Review

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Abstract

The vestibulo-ocular reflex (VOR) causes movements of the eye that are intended to compensate for head and body movements so that vision remains stable on the retina. VOR helps to stabilize the retinal image by rotating the eyes to compensate for movements of the head. The VOR keeps us steady and balanced even though our eyes and head are continuously moving during the performance of actions. The VORs are driven by signals coming from vestibular labyrinths and use subcortical, short-latency pathways from vestibular afferents to the extraocular motor neurons. The relatively simple neural architecture of these reflexive responses, coupled with their stereotyped but adaptable nature, makes them ideal to understand simple sensorineural transformations. Without VOR, when an individual walks down the street, it is difficult to read signs or even recognize faces. Even an inaccurate VOR can result in a slip of visual image concerning photoreceptors, causing blurring of the images. If the VOR is injured, the retinal slip occurs which causes instability in gaze during rapid head movements. The disruption of the VOR results in oscillopsia and abnormal nystagmus. Oscillopsia causes blurred vision when the head is in motion and objects appear to jiggle and bounce as this object does not fix at one point in the retina. The objective of this review article is to discuss the anatomy of VOR with its bedside examinations, clinical implications, and management of VOR failure.

Keywords: Eye, labyrinth, nystagmus, vestibulo-ocular reflex

Introduction

The vestibulo-ocular reflex (VOR) is an involuntary reflex that stabilizes the visual field and retinal image during the motion of the head by producing eye movements in a counter direction.[1] VOR uses information from the vestibular labyrinth of the inner ear to produce eye movements that stabilize the gaze during head movements.[1] The brain constantly monitors the ocular motor control and shows a remarkable ability to adapt the VOR to new visual circumstances. VOR assures clear vision when the head moves. When an individual moves his/her head, the eyes rotate effortlessly so that the world does not appear to move in the opposite direction. VOR adapts so that eye movements have the appropriate magnitude. Climbing nerve fibers provide signals about the slippage of the image on the retina.[2] The rotational VOR (rVOR) generates a slow phase eye movement that compensates for horizontal (yaw), vertical (pitch), or torsion (roll) head rotations.[2] The normal rVOR is compensatory in direction and speed during yaw and pitch head rotations. The effectiveness of the rVOR is usually characterized by its gain, which is defined as the ratio of the velocity of the nystagmus slow phase over the velocity of head rotation.[3] The translational VOR occurs due to the activation of the otolith afferents in the inner ear. It denotes the functional equivalent of the rVOR during translation, although its properties are geometrically more complex than those of rVOR.[3] The purpose of this review article is to discuss the clinical anatomy of VOR with its bedside examinations, clinical implications, and management of the VOR failure.

Methods of Literature Search

Multiple systematic methods were used to find current research publications on the VOR. We started by searching the Scopus, PubMed, Medline, and Google Scholar databases online. A search strategy using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines was

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developed. This search strategy recognized the abstracts of published articles, while other research articles were discovered manually from the citations. Randomized controlled studies, observational studies, comparative studies, case series, and case reports were evaluated for eligibility. There were a total number of 62 articles (21 case reports, 18 cases series, and 23 original articles) [Figure 1]. This article focuses only on the VOR. This review article describes comprehensively the VOR. This review article provides a better understanding of the VOR and its clinical implications. Surely, it will catalyze additional studies into VOR and its clinical implications.

Clinical Anatomy of Vestibulo-ocular Reflex

The basic neural connections of VOR are given by three neuron arcs, namely, a primary sensory afferent neuron whose body sits in the Scarpa's ganglion (the vestibular nerve), a vestibular nucleus neuron at the pontomedullary area, and an oculomotor neuron in the III, IV, or VI nuclei at the brainstem.[4] The vestibular labyrinth consists of three semicircular canals (SCCs) (angular acceleration) and two otolith organs (utricle and saccule for linear and gravitational acceleration sensors) which describe the complete three-neuron arc connectivity. The VOR is under powerful cerebellar control. The cerebellum and interconnected brainstem nuclei, prominently the perihypoglossal nuclei in the medulla, are also components of a polysynaptic vestibular ocular network often called the velocity storage system.[4] This velocity storage system act as an integrator which extends the duration of the horizontal vestibular ocular response and usually allows for a better compensatory VOR response to rotational stimuli of low frequency. The cerebellar and brainstem circuits make an important interaction between vestibular ocular-motor and visual-ocular-motor mechanisms, such as optokinetic nystagmic responses, takes place. The visual input has profound influences on the vestibular function.

Vestibulo-ocular Reflex

The VOR is a simple and phylogenetic old reflex that involves three neuronal pathways. The first neuronal pathway goes from peripheral vestibular organs to the vestibular nuclei (medial, lateral, superior, and inferior).[5] The second neuronal pathway goes from vestibular nuclei to the oculomotor nuclei, and the third pathway reaches the extraocular muscles [Figure 2]. The VOR operates by generating eye movements at the same speed but in the opposite direction of head movement. The function of VOR is to stabilize the image on the fovea during head movement, thus helping the person to see a sharp and clean image even during the movement. The latency period of this reflex is only 8–12 ms, so it is considered the fastest in humans.[6] The VOR arc involves the maintenance of a stable visual field which include extraretinal signals about the head motion, retinal signals, neurocontrol of stabilization reflexes, and motor apparatus (extraocular muscles).[7] The vestibular signals are generated in the membranous labyrinth of the inner ear, which contains two types of sensors, the SCCs, and the otolith organs. The three SCCs elicit angular acceleration of the head in the space, whereas two otolith organs, the utricle, and saccule, detect head tilt and translational acceleration of the head.[8] This vestibulo-ocular reflex keeps us steady and balanced through our eyes when the head is moving continuously when we perform our actions. When the head moves, the eye muscles are triggered instantly to create an eye movement opposite to that of our head movement at the same speed to readjust the visual world, which, in turn, stabilizes our retinal image by keeping the eye still in space and focused on an object, despite the head movement. During the VOR, the endolymph moves in the opposite direction of head movement, causing deflection of the ampulla, which in turn produces afferent action potentials in the primary vestibular nerve.[9] In response to this impulse, the vestibular nucleus generates

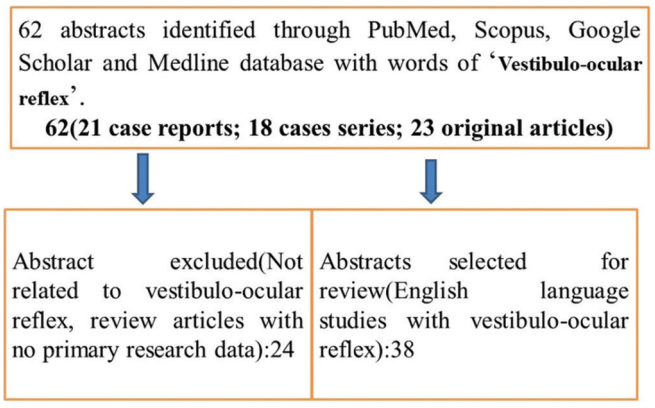

Figure 1: Flowchart showing methods of literature search

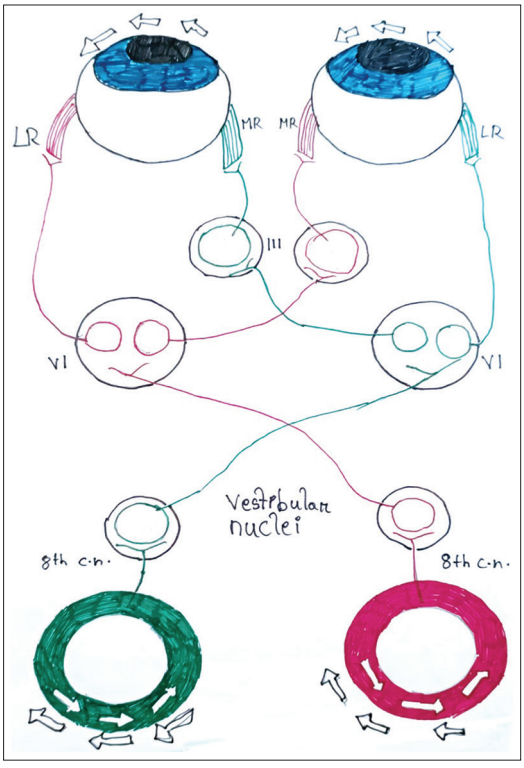

Figure 2: Neural pathway of the vestibulo-ocular reflex

an action potential in the extraocular muscles, leading to eye movement. Thus, an accurate assessment of VOR function is important for vestibular rehabilitation.

Extraretinal Signals for Vestibulo-Ocular Reflex

The vestibular system includes SCCs that transduce angular motion as occurs at the time of rotation of the head. The otoliths (utricle and saccule) transduce linear motion of the head at the time of head tilt and roll.[10] The angular acceleration of the head stimulates the hair cells of the SCCs and leads to eye rotations that are roughly opposite and equal to the head's motion; this stabilizes the reflex which has a brief latency of 7–15 ms and is accurate for head turns at velocities over 300° s.[11] The rotations of the head about the horizontal, vertical, and nasal-occipital axes produce VORs with horizontal, vertical, and torsional counter-rotations of the eye, found as the slow phase of the nystagmus.[12] These reflex eye movements usually must maintain a stable retinal image to be effective. However, the axis of head rotation is the neck and not the center of the eye, so the eye rotates and translates as well. This enhances during near vision, hence the gain of the VOR increases with convergence, leading to more eye movement than head movement.[13] However, the VORs are far from perfect, and yet the objects appear stable during rotation of the head without oscillopsia, which shows that supranuclear foci of the visual system anticipate residual retinal image motion happening due to the inaccuracy of the compensatory eye movements during rotation of the head and corrects for the same.

Retinal signals

The rotation of the head produces retinal image motion of the visual field, which stimulates reflex eye movements with a slow phase following the moving field interrupted by resetting saccades. This reflex is called optokinetic nystagmus, and this complements the VOR during low-velocity sustained head movements such as walking.[14]

Neuro-control of stabilization reflexes

The three SCCs are the end organs that convert the head motion signals into a neural stimulus driving VOR. In the horizontal SCCs, the hair cells undergo depolarization when the endolymph moves toward the ampulla and vice versa in the vertical SCCs.[15] The superior SCC of one side pairs with the posterior SCC of the other side. Stimulation of one canal causes inhabitation of the opponent canal. The three SCCs lie in the same plane as the extraocular muscles. Thus, the lateral SCC lies in the plane of the lateral and medial recti; the left anterior SCCs and right posterior SCC are parallel to the muscle planes of the left eye vertical recti and right eye obliques and vice versa.[16] Each SCC excites a pair of muscles and inhibits a pair of muscles in its plane. For example, the impulses from the left medial vestibular nucleus pass through the right abducens nucleus causing abduction of the right eye and left eye's medial rectus via the oculomotor nucleus (through interneuron connecting abducens and oculomotor nucleus), causing left eye adduction resulting in conjugate eye movements.

Motor apparatus

There are four rectus muscles and two oblique muscles that perform eyeball movements, depending on the stimulation of SCCs and otoliths.

Vestibulo-ocular Reflex Pathology

It is vital to carefully assess eye movements during the clinical examination as the physiological and anatomical substrate of the ocular motor system is intimately connected to the vestibular system through VOR. The VOR is responsible for the development of nystagmus in patients.[17] Caloric stimulation is important and gives the clearest analogy to what an individual experiences in pathological vertigo and nystagmus. When warm water stimulation of the left ear occurs, it increases neural activity from the left lateral SCC and so in the left vestibular nerve; it thereby produces not only left-beating horizontal nystagmus but also a sense of turning about the body's long axis, toward the left. Conversely, cold water stimulation of the right ear decreased the neural activity in the right lateral SCC, the right vestibular nerve, and by commissural disinhibition, it also increases neural activity in the left vestibular nucleus and so produces left beating nystagmus and a sense of turning to the left (the nystagmus always beating toward the side of the higher vestibular activity).[18] In patients with sudden unilateral loss of peripheral vestibular function as in vestibular neuritis, the situation is in some way analogous to cold caloric stimulus. Pathological unilateral increase in vestibular activity is seen in benign paroxysmal positional vertigo (BPPV) which is the most common peripheral vestibular disorder.[15] With proper positioning, there is a sudden brief increase in activity from one SCC. The result is a sudden intense sense of self-rotation in the plane of activated SCC and a nystagmus beating in this plane. If a patient of left posterior canal BPPV is rapidly placed in the provocative left lateral position, there is a sense of self-rotation in a plane halfway between the roll and the pitch plane toward the patient's left side with vertical-torsional nystagmus beating upward and with torsional component toward the lower ear.[19]

Clinical Implications

The disruption of VOR results in clinical presentations such as nausea, head tilt, imbalance during walking, and other life activities, dizziness, oscillopsia, and blurred vision during motion.[20] The VOR is examined by using different methods such as the head impulse test, rotational chair test, velocity step test, impulse angular acceleration, and caloric reflex test. In the caloric reflex test, the external auditory canal is irrigated with 20–40 ml of ice water, leading to slow movements of the eyes toward the ear irrigated and corrective horizontal nystagmus toward the contralateral ear under normal physiological conditions.[21] This reflex is usually damaged in case of brain stem injury. Persons with VOR malfunction are likely to be clumsy, get motion sickness easily, have difficulty maintaining balance, have sensory issues, and have nausea. If the sensory vestibular organs are not fully functional on either side, the

brain will get conflicting signals related to the movements, leading to vertigo.[22] Diseases of the VOR can be classified as per three major planes of action, yaw plane, pitch plane, and roll plane, which equate with horizontal nystagmus, upbeat or downbeat nystagmus, and torsional nystagmus, respectively.

Examination of Vestibulo-ocular Reflex

Bedside examination

Diagnosis of dizzy patients remains a daunting challenge for clinicians despite modern radiological investigations and increasingly sophisticated electrophysiological testing. Dynamic visual acuity (DVA) and video head impulse tests are clinical tests to measure VOR.

Dynamic visual acuity

With normal VOR, there is little difference in visual acuity when the head is tilted or moving. In the case of vestibular hypofunction, there is marked degradation of the visual acuity and illusory movement of the environment (oscillopsia) while the head is rotating.[23] This is the rationale for comparing visual acuity with head movement. DVA is evaluated while the head is oscillated horizontally, vertically, or in the roll plane (from ear to shoulder) at a relatively high frequency of about two cycles per second.[23] In this frequency, visual tracking systems are too sluggish to provide much gaze stability, and so the function of rVOR can be evaluated acting alone, almost as if one was testing it in the dark.

Headshaking-induced nystagmus test

Headshaking-induced nystagmus (HSN) is a sign of a dynamic imbalanced vestibular function. The bedside HSN test is usually performed in patients wearing Frenzel lenses. The head of the patient is rotated within a comfortable range at a frequency of about 3 cycles per second for about 10 s and an induced nystagmus is observed after the head has stopped moving. With a one-sided vestibular function loss, a vigorous nystagmus with slow phases directed initially toward the affected side usually appears, sometimes followed by a reversal phase with slow phases directed toward the intact side.[24] In the case of unilateral labyrinthine loss, there is an asymmetry of the peripheral vestibular inputs during high-velocity head rotations (Ewald's second law), which leads to an unequal accumulation of activity in the central velocity storage mechanism in the vestibular nuclei. Just after headshaking, the initial phase of HSN appears due to the decay of activity within the velocity storage mechanism. A reversal phase may appear with slow phases directed toward the intact labyrinth (i.e., biphasic HSN). This reversal of the HSN shows a short-term adaptation mechanism that balances out the initial phase. The biphasic conversion of headshaking is correlated with the severity of the initial SCC paresis.[24] Monophasic HSN indicates less severe vestibular hypofunction than biphasic nystagmus.[23] HSN may be seen with central lesions, usually in the cerebellum and medulla.[25] A cross-coupled perverted HSN-like vertical nystagmus following horizontal headshaking is almost a feature of a central and often a cerebellar disturbance, though focal brain stem lesions with involvement of the crossed ventral tegmental tract may manifest this pattern.[26]

Valsalva-induced nystagmus

The Valsalva maneuver can induce nystagmus either by raising the intracranial pressure or by increasing the middle ear pressure.[27] The nystagmus may be induced in patients with craniocervical junction anomalies like Arnold–Chiari malformation with perilymph fistula, or superior canal dehiscence. In the fistula test, compression of the tragus can also provoke nystagmus by changing the middle ear pressure (Hennebert's sign). Jugular venous compression can also increase intracranial pressure and induce nystagmus similar to the Valsalva maneuver.[27] Tullio's phenomenon (noise-induced nystagmus and oscillopsia) usually occurs in patients who have Valsalva-induced nystagmus and is often associated with superior canal dehiscence.[28]

Multiple sclerosis and vestibulo-ocular reflex

Multiple sclerosis (MS) is a progressive disease that affects the central nervous system. VOR function is processed in the central vestibular nuclear complex of the brainstem and then the cerebellum modulates it. The defect in VOR can be a preliminary sign of MS or become apparent later.[29] The visual pathway is highly susceptible to injury in MS. This explains the relevance of visual impairment in MS, being the second cause of life quality loss in this type of patient. VOR is an important component of the visual function. Any abnormality in VOR affects the stabilized gaze on the target during head movement. In MS, the gaze changes along with head movements and there is a requirement of compensatory saccades for fixation on the target.[30]

Hyperventilation-induced nystagmus

Hyperventilation may induce the symptoms in patients with anxiety and phobia but often does not induce nystagmus. Patients with demyelinating lesions of the vestibular nerve due to compression by a tumor or small blood vessels (microvascular compression) or with demyelination in central neural pathways as in MS may develop nystagmus with hyperventilation. Hyperventilation may induce nystagmus in patients of vestibular neuritis in the case of acute stage as well as in the compensated stage.[31] Hyperventilation can enhance spontaneous downbeat nystagmus in cerebellar lesions which is likely mediated through metabolic effects on the calcium channels of Purkinje cells.[32] Moreover, the hyperventilation may aggravate nystagmus by changing intracranial pressure in patients with craniocervical junction anomalies or with an abnormal connection between subarachnoid space and labyrinth as occurs with a perilymph fistula.

Management of Vestibulo-ocular Reflex Failure

Presently, there is no effective treatment for bilateral vestibular deficits.[33] The research efforts on animals and humans in the last decade set a solid background for the concept of using electrical stimulation for restoring the vestibular or VOR

function.[34] The potential benefits of vestibular neuroprosthesis for restoring VOR failure are still in the clinical trial. VOR can be artificially restored in humans by using motion-controlled, amplitude-modulated electrical stimulation of the ampullary branches of the vestibular nerve.[35] Modified cochlear implants with vestibular electrodes are prototype vestibular neuroprosthesis helpful to restore the vestibular or VOR failure.

Conclusion

The vestibular system plays an important role in the multisensory control of balance. The VOR is the only system that maintains stable vision during rapid rotations of the head. VOR keeps the person in balanced and steady position through the eyes when the head is moving continuously during performing the most actions. When the VOR is lost, essential tasks such as gaze stabilization is limited and the quality of life of the patient is significantly impaired.

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Conflicts of interest

There are no conflicts of interest.

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