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Vestibular System

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Reading: Purves et al. (2008, 4th edition), Neuroscience, Chapter 14.

Goals: The goals are to understand how the hair cells communicate the sense of dynamic and static head position, and how this information is transmitted to the brain to control posture and eye position.

Introduction.

The vestibular system could be described as a silent system. You do not know that it is operating until something goes awry. As you will learn, its silence in no way undermines its importance. Without this system, you probably could not perform simple tasks such as walking, standing, and looking.

Peripheral Vestibular Apparatus.

The vestibular system serves three primary functions:

1. **Head position:** It plays a dominant role in the sensation of motion and spatial orientation of the head.

2. **Posture:** The vestibular apparatus plays a major role in adjusting muscular activity to maintain posture and balance.

3. **Stabilization of visual images:** it plays a role in stabilizing the fixation point of the eyes when the head moves--providing a stabilized image on the retina.

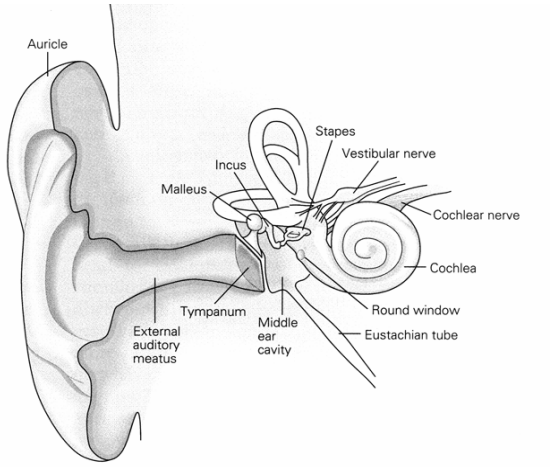

Figure 1: Illustration of the human ear and the relationship between the vestibular and cochlear apparatus. The vestibular apparatus is posterior to the cochlear apparatus.

Thus, the vestibular system interacts intimately with the visual-motor, and proprioceptive systems to accomplish the above functions. Collectively, the three systems are called the "equilibrial triad". To understand how it does this, it is necessary to examine the receptor characteristics of the peripheral vestibular apparatus.

Figure 1 illustrates the human ear and the relative positions of the cochlea and vestibular apparatus. Relative to the cochlea, the vestibular apparatus occupies a posterior position. Both structures reside in the temporal bone.

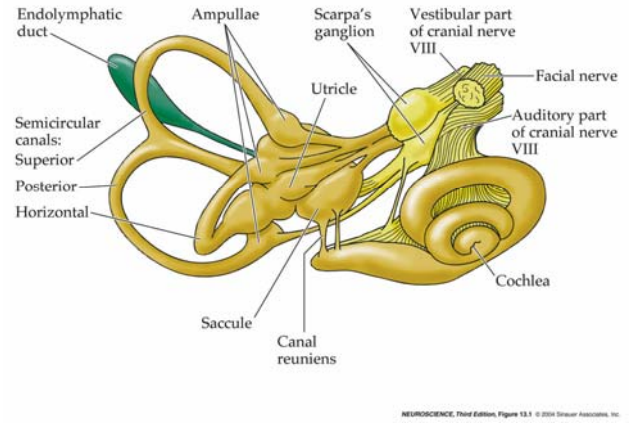

Figure 2. The vestibular apparatus

Figure 2 illustrates the gross features of the vestibular apparatus. It is made up of canals and caves and hence the name "labyrinth". The walls of these labyrinths are the surrounding bone (bony labyrinth) and an inner membrane wall (membranous labyrinth). The space between the bony and membranous labyrinth is filled with cerebrospinal fluid and is called perilymph. This space is continuous with the subarachnoid space and the communication is through a tiny canal in the temporal bone. The membranous labyrinth is also filled with fluid called endolymph It is high in potassium ions and resembles intracellular fluid. Although the membranous labyrinth is a continuous structure, five distinct areas can be recognized. The three looped tunnels due to their shape are called semicircular canals and are oriented approximately 90 degrees to each other (horizontal or lateral, superior or anterior, and posterior or vertical). The two cavernous structures are individually referred to as the utricle and saccule and are collectively referred to as the otolithic organs. These five distinct structures each has a highly developed neuroepithelium where the receptors reside. The receptor regions of the semicircular canals reside in a dilated portion called the ampulla, and since the receptors are arranged in a crest-like manner, the receptor area is called cristae ampullaris. The receptor area for the utricle and saccule reside in a sheet-like area called the macula.

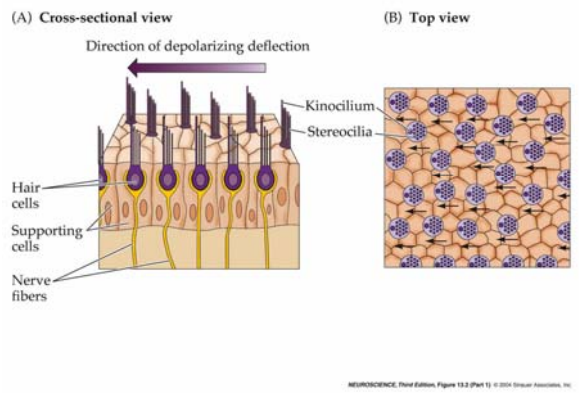

Figure 3. Polarization of vestibular hair cells

Hair Cell Transducer Properties.

The sensory receptors are hair cells (Figure 3) that are divided into two categories : Type I and II. The type I hair cell is probably akin to the inner hair cells of the cochlea and is the primary sensory

transducer. Type II closely correspond to the outer hair cells of the cochlea. Each of the hair cells has about 100 stereocilia (modified microvilli) which systematically decrease in length as a function of the distance from the kinocilium. Each hair cell has a single kinocilium (modified cilia) which is approximately 40-70 microns long.

The arrangement of the stereocilia in reference to the kinocilium has function significance.

1. Movements of the stereocilia towards the kinocilium produce a depolarization of the hair cell and excitatory discharges in the afferent fiber.

2. Movement away from the kinocilium results in hair cell hyperpolarization and a corresponding suppression of discharge levels is observed.

3. Movements orthogonal to the excitatory-inhibitory plane do not yield any changes in membrane or action potentials.

4. Movements between those aligned and orthogonal to the kinocilium produce submaximal depolarizations and hyperpolarizations . Thus, a hair cell not only responds to movements aligned with the kinocilium but also to any movements that have a vector component in this direction.

Thus, the hair cell is a exquisite directional sensor and the kinocilium establishes its polarity. However, the kinocilium itself does not seem to be involved in the actual generator mechanisms. For example, when only the kinocilium is moved, no responses are evident. Removing the kinocilium also has no affect on the directional properties of the hair cell. Possibly during development, the kinocilium provides the polar coordinates for stereocilia organization, but once this is established, it no longer plays a functional role.

Hair Cell Organization: Macula.

Examination of the sensory epithelium reveals high degree of hair cell organization that has functional import. Figure 4 shows the sensory epithelium of the macula. Here, the hair cells are embedded in a sheet of jelly-like proteinaceous material. Calcium carbonate crystals called

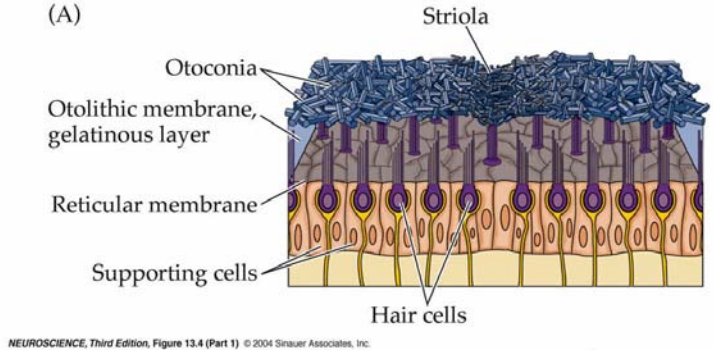

Figure 4: Sensory epithelium of the macula. The cilia of both types of hair cells protrude into an overlying gelatinous sheet called the otolithic membrane. Embedded in this sheet are calcium carbonate crystals called otoconia. Movement of this sheet creates a shearing motion on the stereocilia.

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otoconia or otolith (hence the name otolithic organs) are embedded in this material. It can be easily imagined that head movement or static gravity would influence these dense particles and provide a shearing force on the embedded stereocilia.

Another level of organization of the macular organs is illustrated in Figure 5. This schematic depicts the relative positions of the utricle and saccule in the vestibular apparatus (right side), the orientation of the utricle (right upper) and saccule (right lower), and the axes of polarization of their hair cells. The arrows represent the functional polarization of the hair cells (movement in the direction of arrow is excitatory and opposite movement is inhibitory). The hair cells are organized as functional pairs along a line called the striola. Thus, within a pair, when one hair cell is excited the other is inhibited. This organization is further displayed in Figure 6 for hair cells in the utricle. In this example, the head is tilted in the upward direction. Gravitational forces and the mass of the otolithic membrane filled with otoconia causes it to slide downward. Consequently, the stereocilia of the hair cells on one side of the Striola are bent towards the kinocilium causing the hair cell to be depolarized. This excites the vestibular afferents. The stereocilia on the other side of the Striola are bent away from the kinocilium causing the hair cell to hyperpolarize. This inhibits their vestibular afferent. Since the line of Striola is curved (Fig. 5), their exists function pairs of hair cells that can sense any position of the head relative to the body axis.

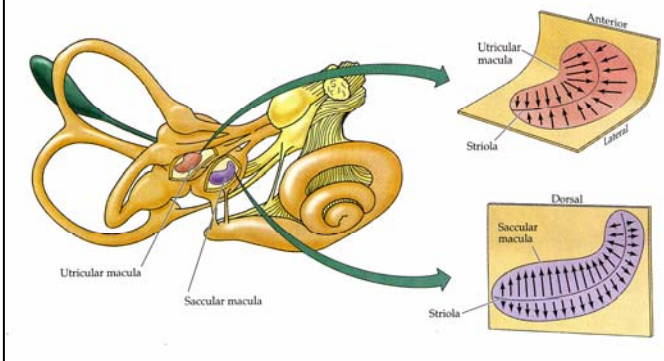

Figure 5: The relative positions of the utricle and saccule and the axes of polarization of their hair cells. The arrows represent the functional polarization of the hair cells (movement in direction of arrow is excitatory and opposite movement is inhibitory. Note that the hair cells are organized as functional pairs along a line called the striola. Thus, within a pair, when one hair cell is excited the other is inhibited.

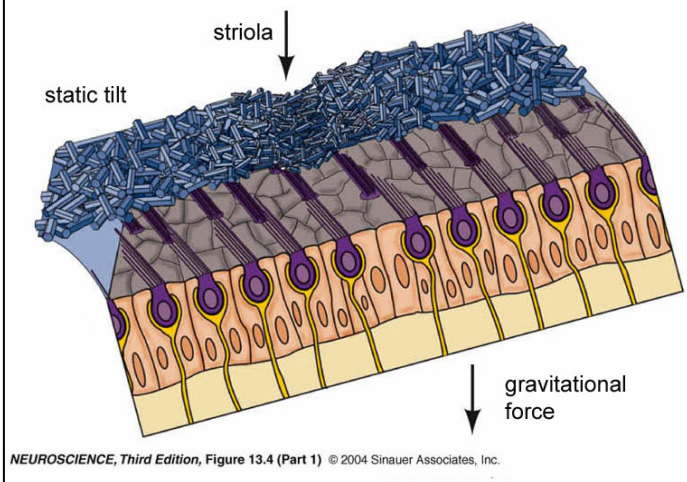

Figure 6: Functional organization of the hair cells in the macular organs. In this example, an upward tilt of the head causes the otolithic membrane to slide backwards. The stereocilia of the hair cells on one side of the striola are bent towards the kinocilium causing the hair cell to be depolarized. This excites the vestibular afferents. The stereocilia on the other side of the striola are bent away from the kinocilium causing the hair cell to hyperpolarize. This inhibits their vestibular afferent.

The anatomical organization of the macular organs (utricle and saccule) makes it an ideal sensor of static head position. Figure 7 shows the response of a utricular afferent to an upward and downward tilt of the head.

The following observations can be made:

1. There is a high level of discharge at resting levels. In this example it is approximately 40 spikes/sec when the head is in its normal position (e.g., 0 degrees tilt). This is a characteristic feature of vestibular nerve fibers. This feature increase the dynamic range of movement sensitivity by allowing firing levels below and above the resting level. If there were no spontaneous activity, only movements towards the kinocilium (excitation) could be coded.

2. When the head is tilted upward the discharge rate increases above the resting level and is maintained for the duration of the tilt. When the head is tilted downward the discharge rate decreases below the resting level and is maintained for the duration of the tilt. Thus, this single macular afferent can signal to the central nervous system whether the head is tilted upward or downward and how long this position was maintained.

3. The magnitude of the tilt are coded by graded changes in the firing rate. For example, compared to the responses in Figure 7, a smaller upward tilt would results in less firing above the resting level and a smaller downward tilt would result in less of a suppression below the resting level.

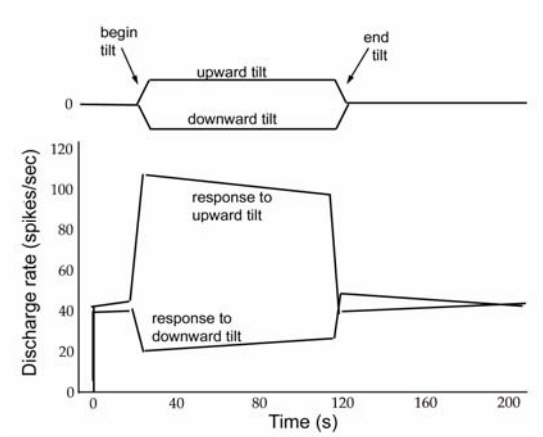

Figure 7: Schema of responses of a utricular afferent to upward and downward tilt of the head**.** The upper part depicts the direction and duration of the head tilt and the bottom part reflects the discharge of a single utricular afferent to these two directions of head tilt (adapted from Purves et al., Neuroscience, 20084, p. 351).

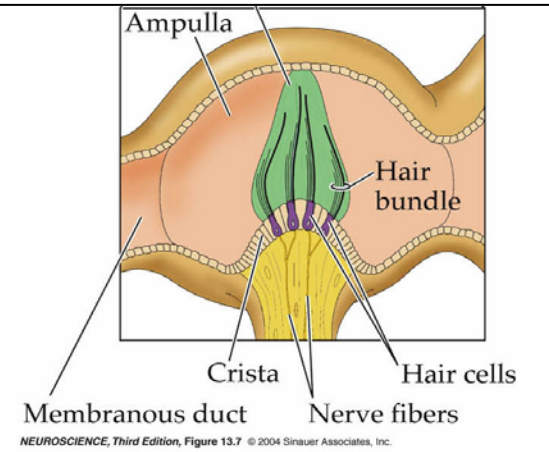

Figure 8: Sensory epithelium of the ampulla. The cilia of both types of hair cells are embedded in a gelatinous mass called the cupula. The cupula impedes the movement of the endolymph through the semicircular duct. Movement of the cupula in one direction depolarizes, and in the opposite direction hyperpolarizes

In addition to static head position sense, the macular organs play a pivotal role in detecting linear acceleration. For example, sitting in a car or airplane during takeoff (i.e., acceleration) will cause the otolithic membrane to slide backwards, which in turn deflects the stereocilia of the hair cells. The resultant sensation is that of accelerated movement. Once the car or plane has reached a constant speed, the otolithic membrane returns to its normal position and the stereocilia are no longer deflected. This is the reason why it is difficult to know (with eyes closed) if you are moving once the vehicle is traveling at a constant speed.

Hair Cell Organization: Cristae Ampullaris.

For the sensory epithelium of the semicircular canals, the stereocilia are embedded in a gelatinous material called the cupula (Figure 8). All of the hair cells are oriented in the same direction. The hair cells are maximally deflected when the head is rotated about the axis perpendicular to the duct. The actual force for bending the hair cells is provided by the endolymph pushing against the cupula during angular rotation.

Since the hair cells are all oriented in the same way within the cupula, the functional pair organization seen in the macula is not present. Rather the function pair organization is brought about by the relationship between semicircular canal pairs on the right and left side. Figure 9 illustrates this principle. Due to the geometrical arrangement, it works out that for the horizontal canals, rotation about it's axis in one direction creates excitation in one canal and inhibition in the other. For the superior canals, the functional pair is the posterior canal on the opposite side.

Figure 10 illustrates the responses of a semicircular canal afferent to angular acceleration and deceleration. The following observations can be made:

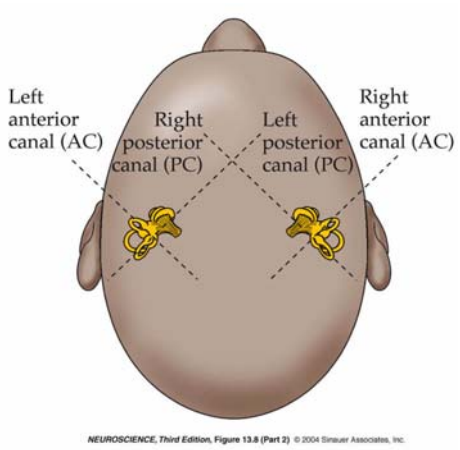

Figure 9: Functional organization of the semicircular canals. They are organized as 3 functional, parallel pairs: left anterior-right posterior, right anterior-left posterior, and left horizontal-right horizontal. Rotation that excites hair cells in one canal of a functional pair causes inhibition in the other canal of that pair.

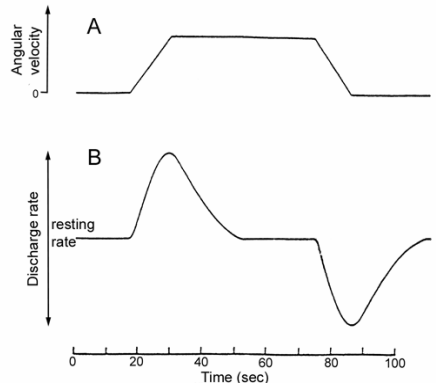

Figure 10: Response of a semicircular canal afferent to angular rotation of the head. The upper trace reflects angular velocity and the lower trace depicts the discharge rate of the afferent fiber. During angular acceleration, the fiber abruptly increases its discharge rate. During constant velocity, the discharge rate returns to resting level. During deceleration, the discharge rate abruptly decreases.

1. During the acceleration phase the endolymph lags, exerting force on the cupula. During this phase, the afferent fiber discharges vigorously.

2. Once acceleration has ceased and the head is rotating at a constant velocity, the endolymph catches up (moves at the same rate as the head) and the force on the cupula is no longer present. During this phase, the neural discharge rate returns to resting levels.

3. During the deceleration phase the endolymph again lags, but in this case the force upon the cupula is opposite to that seen during acceleration. Due to the uniform orientation of the stereocilia in the cupula, a force in the opposite direction should inhibit the discharge, and it does.

In sum, the cristae ampullaris of the semicircular canal seem to be optimized for detecting angular accelerations while the otolithic macula signal static head position and linear acceleration. These two systems combine to provide the central nervous system with both static and dynamic 3-dimensional position information.

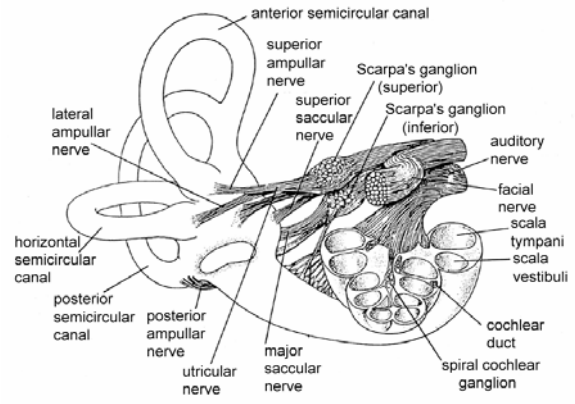

Figure 11: The cell bodies of primary vestibular afferents reside in Scarpa's ganglion. It is comprised of a superior and inferior part. The afferents from the anterior and horizontal canals and from the utricle have their cell bodies in the superior part, while those from the posterior canal and saccule reside in the inferior part.

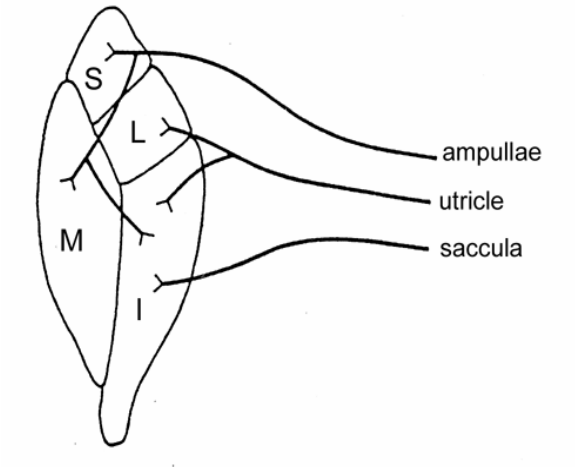

Figure 12: Simplified scheme of the distribution of vestibular afferents to the vestibular nuclei. The lateral (L) nucleus receives input primarily from the utricle. The medial (M) and superior (S) nuclei receive inputs primarily from the semicircular canals. The inferior (I) nucleus receives input from all of the vestibular afferent.

Central Nervous System: Vestibular Anatomy.

The afferents innervating the hair cells have their cell bodies in Scarpa's ganglion. This ganglion is divided into a superior and inferior division (Fig. 12). The afferents from the superior and horizontal canals and utricle have their cell bodies in the superior vestibular ganglion, while the cell bodies of posterior canal and saccule afferents reside in the inferior vestibular ganglion.

The axons of the ganglion cells (approximately 19,000 fibers) form the vestibular part of the VIIIth nerve and enter the upper medulla and inferior peduncle of the cerebellum. Upon entering the brain, the primary afferents bifurcate into short ascending and descending fibers before synapsing in the vestibular nuclei. There are 4 vestibular nuclei and they occupy a large part of the medulla beneath the floor of the fourth ventricle. The vestibular nuclei each has a distinct set of inputs and outputs.

Figure 13 shows the major inputs from the vestibular apparatus to the vestibular nuclei. The lateral vestibular nucleus (Deiter's nucleus) receives a strong input from the utricle and neurons here are exquisitely sensitive to changes in head tilt. This nucleus also has the distinction of being the only nucleus outside the cerebellum to receive direct Purkinje cell input. This input is inhibitory. The inputs to the medial and superior vestibular nuclei derive primarily from the semicircular canals. The inferior or descending vestibular nucleus receives inputs from all of the vestibular apparati, i.e., semicircular canals, utricle, and saccule. Some primary vestibular afferents go directly as mossy fibers via the juxtarestiform body to the flocculonodular lobe of the cerebellum.

Figure 13 illustrates the major output tracts of the vestibular nuclei. Listed below are the major tracts.

1. Lateral vestibulospinal tract: is comprised of axons from neurons in the lateral vestibular nucleus. This pathway is uncrossed and descends the length of the spinal cord in the anterior-lateral funiculi. These fibers have a pronounced facilitating effect on both alpha and gamma motor neurons that innervate antigravity muscles in the limb. This tonic excitation maintains muscle tonus so that an upright body posture is maintained.

2. Medial vestibulospinal tract (MVST): is comprised of crossed and uncrossed fibers from the medial vestibular nucleus. This tract terminates bilaterally in the cervical region. These fibers influence the musculature of the sternocleidomastoid and trapezius via the spinal accessory nucleus. Thus, they participate in the reflex control of neck movements, which in turn maintains accurate head position relative to eye position.

3. Medial longitudinal fasiculus (MLF): is comprised of crossed and uncrossed fibers from the lateral, superior and medial vestibular nuclei which ascend and innervate the extraocular nuclei (oculomotor, trochlear, and abducens). The function of this pathway is to control conjugate eye movement in

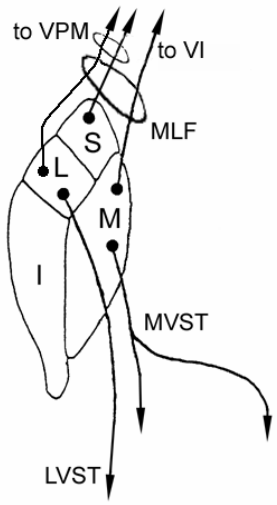

Figure 13: Simplified scheme of major output tracts of the vestibular nuclei

coordination with head movements to maintain visual fixation. Axons from the lateral and superior vestibular nuclei also project to the ventral posterior medial thalamus and the neurons from this thalamic area are represented near the face area in the somatosensory cortex.

4. Cerebellar input: Fibers from the inferior and medial vestibular fibers also enter the cerebellum via the juxtarestiform body and project as mossy fibers to the uvula, flocculus, nodulus, and fastigial nuclei. Within the cerebellum, these fibers are distributed bilaterally with an ipsilateral bias.

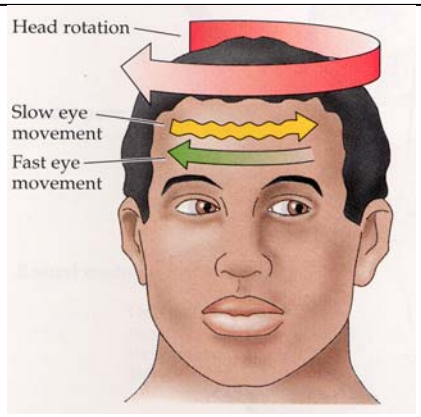

Figure 14: Schematic illustration of the slow and fast phase of nystagmus seen in the vestibuloocular reflex.

Vestibular-Oculomotor Reflex

Vestibulo-oculomotor reflexes (VORs) serve to stabilize visual images during movements of the head. Figure 14 illustrates a VOR mediated by inputs from the horizontal canals. A slow conjugate eye movement occurs in the direction opposite to that of the rotational direction. This is called the slow phase of nystagmus and serves to maintain fixation while the head turns. As the head continues to rotate, at one point, the eyes reach their limit in the orbit and a quick eye movement in the direction of the rotation occurs. This fast reset is called the fast phase of nystagmus.

When the rotation is abruptly stopped, the directions of the slow and fast phase of nystagmus are reversed. This post rotatory nystagmus is caused by the inertia of the endolymph deflecting the cupula in the opposite direction to that created by the initial rotation. This mechanism was explained in Fig. 10.

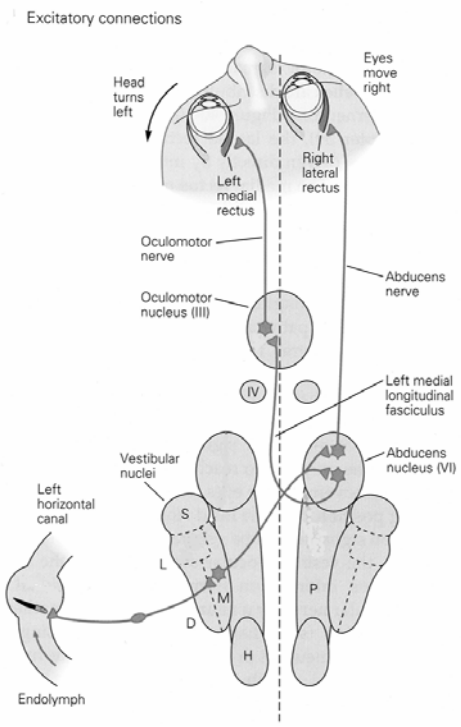

Figure 15: A neural circuit for the slow phase of nystagmus seen in the vestibulo-ocular reflex.

Figure 15 outlines the neural circuit for the slow phase of vestibular nystagmus. As the head is rotated to the left, the endolymph pushes against the cupula and causes the hair cells in the left horizontal canal to depolarize, resulting in increased firing in their afferents. These afferents make excitatory synapses onto neurons in the left (ipsilateral) medial vestibular nuclei. The axons from the medial vestibular nucleus cross the midline and make excitatory synapses onto neurons in the right (contralateral) abducens nucleus, which in turn activate the lateral rectus of the right eye. Some of the axons from the right abducens nucleus cross the

midline, and travel with the left MLF to make excitatory synapses onto neurons in the left (ipsilateral) oculomotor nucleus. The oculomotor neurons then activate the medial rectus of the left eye. The end results of this leftward rotation is to move both eyes rightward (slow phase), a direction opposite to that of the rotation. Of course there is a mirror circuit (not shown) that serves to inhibit the antagonistic muscles of each eye (reciprocal inhibition).

The VOR is used clinically to evaluate vestibular function. The slow phase of nystagmus involves the vestibulo-ocular pathway, while the fast phase is thought to be a cerebral reflex. Comatose patients can display the slow phase of nystagmus, but not the fast phase. This is consistent with a cerebral mechanism for the fast phase since coma always involves cortical dysfunction.

An economical method to assess vestibulo-ocular integrity is the caloric test. Here, hot (50◦ C) or cold (20◦ C) water is squirted into the external ear canal, while the head is so positioned to maximize the stimulation of a particular semicircular canal. The hot or cold fluid create convection currents in the endolymph, which in turn applies force to the cupula. In non-comatose patients the fast phase of nystagmus is easiest to observe. Cold water evokes the fast phase of nystagmus in the direction opposite to the ear stimulated and warm water evokes this nystagmus in the same direction as the stimulated ears. This effect leads to a easily remembered acronym, COWS (cold-opposite, warm-same).

Figure 16 illustrates the use of a cold caloric test on three comatose patients with different brain lesions. Displayed are the slow phase of nystagmus movements since comatose patients do not display a fast phase. Since the slow phase is in the opposite direction of the fast phase, COWS becomes CSWO for the slow phase. The patient with an intact brain stem displays a nystagmus similar to that seen in normals. The patient with a bilateral MLF lesion only displays an appropriate nystagmus in the eye of the same side as the caloric stimulation. The other eye remains stationary. This is because the axons from the abducens to the opposite oculomotor nucleus that travel in the MLF are lesioned. The eyes of the patient with a low brain stem lesion remain stationary. This occurs because either the abducens and/or vestibular nuclei, are destroyed.

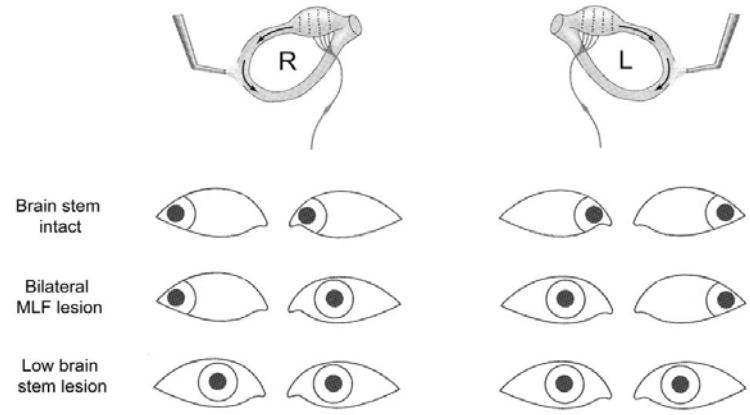

Figure 16: Cold water caloric test that stimulates the horizontal semicircular canals. Displayed is the slow phase of nystagmus for three comatose patients to cold water irrigated into the right (R) and left (L) ear canals. The **upper** pairs of eyes reflect the evoked eye movement in a patient with an intact brain stem, the **middle** in a patient with a bilateral MLF lesion, and the **lower** in a patient with a low brain stem lesion