The Vestibular System-Caloric Reflex Test and Horizontal Gaze Nystagmus Test

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Integration of vestibular input, vision, and proprioceptive feedback is instrumental in maintaining orientation and balance of the body in both static and kinetic environment. In this article, a prelude to organization of the vestibular system is followed by a discussion on caloric test and control of horizontal gaze.

Organization of the Vestibular System

The **vestibular system** is the sensory system that provides the leading contribution to the sense of balance and spatial orientation for the purpose of coordinating movement with balance. The end organs of the vestibular system dwell in the membranous labyrinth in the **inner ear** sited in the petrous part of the temporal bone. Final integration of vestibular information is the function of cerebellum, thalamus, and somatosensory cortex.

Vestibular Labyrinth and Semicircular Canals

The membranous labyrinth is contained in the bony labyrinth and comprises of the **cochlear duct** and the vestibular labyrinth. The vestibular labyrinth is formed by the

otolith organs and the **semicircular canals**. As movements consist of rotations and translations, the vestibular system comprises two components: the semicircular canal system, which indicates rotational movements; and the otoliths, which indicate linear accelerations.

There are **3 mutually orthogonal semicircular canals**: lateral (horizontal), anterior (superior) and posterior (inferior). The anterior and posterior semicircular canals are collectively termed as “vertical“ canals.

Each semicircular canal is designed to sense **angular acceleration** in a particular axis perpendicular to its orientation in space. Thus, the **horizontal** canal detects motion in the vertical axis, like **rotating the head** to say ‘no’, while the **anterior** semi-circular canals perceive acceleration in the sagittal plane. This occurs, for example, when nodding your head (anteroposterior movement). The **posterior** semicircular canal detects rotation of the head around a rostral-caudal (anterior-posterior) axis, or in other words rotation in the coronal plane. This occurs, for example, when the head moves to touch the shoulders), or when doing a cartwheel.

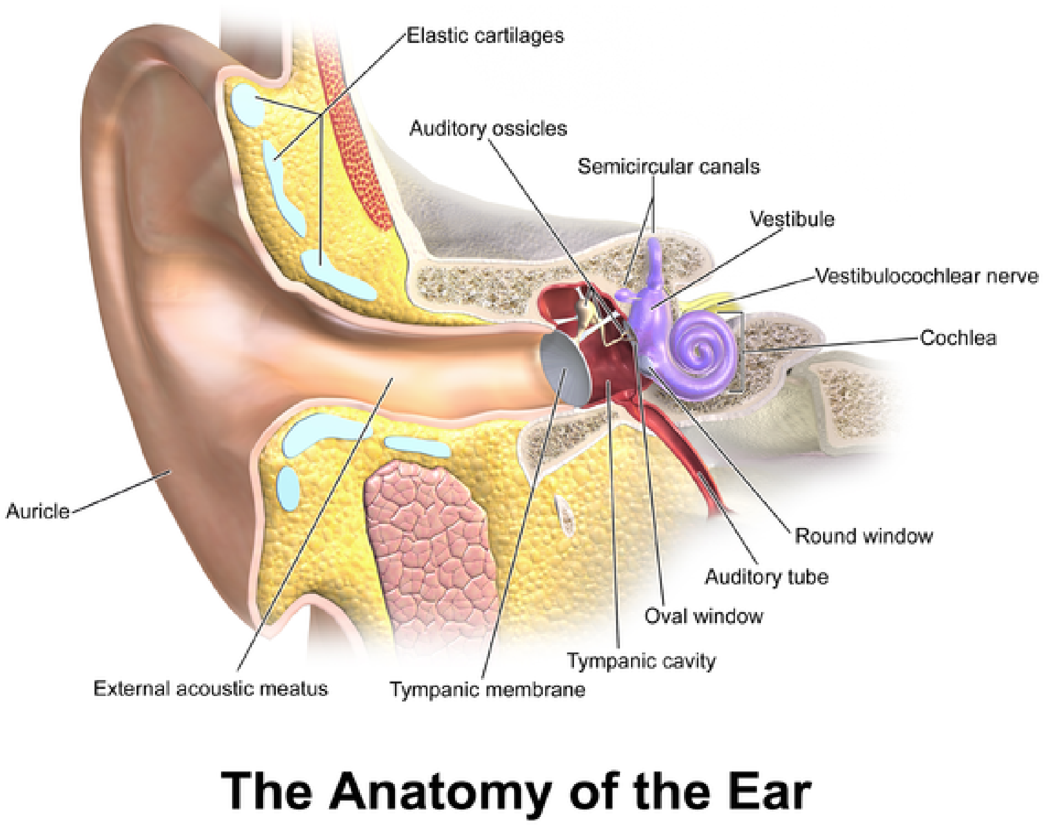


Image: “Anatomy of the Ear.” by Blausen.com staff. “Blausen gallery 2014”. Wikiversity Journal of Medicine. DOI:10.15347/wjm/2014.010. ISSN 20018762. – Own work. License: CC BY 3.0

The horizontal canal is oriented at about 30 degrees from the horizontal axis, while the vertical canals are aligned at right angles to each other.

Each semicircular canal has a dilated end called **ampulla**. Each ampulla nests an elevated crest is known as **crista ampullaris**, which consists of hair cells with an overlying thick gelatinous cap termed as the **cupula**.

Each semicircular canal contains **endolymph**. The hair cells consist of a single **kinocilium** surrounded by about 40-70 **stereocilia**. The motion of the stereocilia relative to the kinocilium determines the **polarity of the hair cell**.

Movement of the endolymph during angular acceleration results in bending of the cupula against the hair cells. Subsequently, the stereocilia move toward the kinocilium and the hair cells of the crista ampullaris will depolarize with consequent activation of the **vestibular nerve fibers**.

The canals on the two sides work in a complementary counter-regulatory mode. Also known as the **push-pull system**, it encompasses **crossed coupling of the canals**. Excitatory stimulus for anterior canal on one side curbs signals from the contralateral posterior canal. This arrangement ascertains detection of motion in a very specific and sensitive manner.

Utricle and Saccule (Otolith Organs)

The otolith organs are present in the **vestibulum**. The **saccule detects vertical acceleration**, whereas **the utricle responds to acceleration in the horizontal plane**.

The sensory epithelium is known as **macula**. The macula consists of hair cells, kinocilium, and stereocilia as in the semicircular canals, with an overlying fibrous membrane called **otolithic membrane**.

The presence of **entrenched calcium carbonate crystals "otoconia"** gives the latter its name. Shearing forces generated by relative motion between the otolithic membrane and the hair cells stimulate the nerve endings.

Gravity and linear acceleration set the otolith organs to work, whereas angular acceleration stimulates the semicircular canals.

Vestibular Nerve

A part of the **VIII cranial nerve**, the vestibular component of the **vestibulocochlear nerve** emanates from the bipolar cells in the **vestibular ganglion of Scarpa**.

Axons travel to the **vestibular nucleus** in the floor of the fourth ventricle through superior and inferior vestibular nerves.

The superior vestibular nerve mediates information from the **utricle**, **superior and lateral semicircular canals**. The inferior vestibular nerve conveys information from the **saccule**. Equivocal evidence of existence of a **posterior branch** from the posterior semicircular canal exists.

Vestibular Nucleus

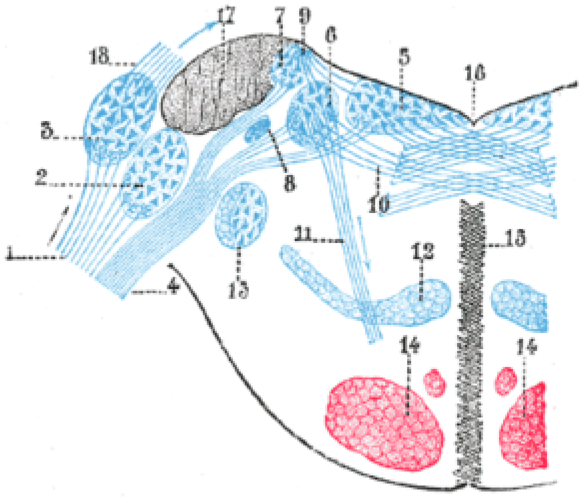


Image: "Terminal nuclei of the vestibular nerve, with their upper connections. (Schematic.) 1. Cochlear nerve, with its two nuclei. 2. Accessory nucleus. 3. Tuberculum acusticum. 4. Vestibular nerve. 5. Internal nucleus. 6. Nucleus of Deiters. 7. Nucleus of Bechterew. 8. Inferior or descending root of acoustic. 9. Ascending cerebellar fibers. 10. Fibers going to raphé. 11. Fibers taking an oblique course. 12. Lemniscus. 13. Inferior sensory root of trigeminal. 14. Cerebrospinal fasciculus. 15. Raphé. 16. Fourth ventricle. 17. Inferior peduncle. Origin of striæ medullares. (Testut.)" by Henry Vandyke Carter, Henry Gray (1918) Anatomy of the Human Body. Bartleby.com: Gray's Anatomy, Plate 761 License: Public Domain

There are 4 vestibular sub-nuclei:

1. Superior vestibular nucleus: **Nucleus of "Bechterew"**
2. Inferior vestibular nucleus: **Spinal nucleus**
3. Lateral vestibular nucleus: **Nucleus of Deiter**
4. Medial vestibular nucleus: **Nucleus of Schwalbe**

Lateral to the **sulcus limitans** in the floor of the fourth ventricle, the superior and lateral nuclei are positioned in the **pons**, while the inferior and medial nuclei are situated in the **rostral medulla**.

Central Pathways

The central connections from the vestibular nuclei can be tabulated as follows:

Tract	Description
Medial vestibulospinal tract	The major descending tract from the medial vestibular nucleus to the dorsal spinal cord traversing through the medial longitudinal fasciculus; it **coordinates head movements**.
Lateral vestibulospinal tract	Originating from the lateral vestibular nucleus, it descends to the sacral cord and is instrumental in **maintaining posture**.
Medial longitudinal fasciculus	**Ascending tracts from the superior and medial vestibular nuclei reach the oculomotor nuclei (cranial nerves III, IV and VI) to bring about coordinated eye movements.**
Vestibulocerebellar tract	There are reciprocal connections between the archicerebellum; the "flocculonodular lobe" and the vestibular system, which **modulates motor activity while simultaneously maintaining balance.**

Vestibulothalamic projection	En route to the somatosensory cortex, these fibers relay in the ventroposterior intermedius (VPI) nucleus of the thalamus. They transmit **conscious perception of gravity and motion.**

Caloric Reflex Test

Described by **Robert Barany in 1906**, the caloric reflex test is a test of **responsiveness of the lateral semicircular canals**. The objective **"electronystagmography"** test battery comprises of oculomotor evaluation, positioning test, and the caloric test.

Test methodology

There are many variants of this test. The oldest and classically described is the **bithermal stimulation test**. Hot and cold water irrigation is sequentially carried out in each ear.

The patient is positioned with his head inclined to about 30 degrees to make the lateral semicircular canal horizontal. Water is designated "hot" when it is about 7 degrees above body temperature and "cold" for about 7 degrees below body temperature. The irrigation is stopped after about 30-40 seconds and one looks for nystagmus while deliberately diverting the attention of the patient.

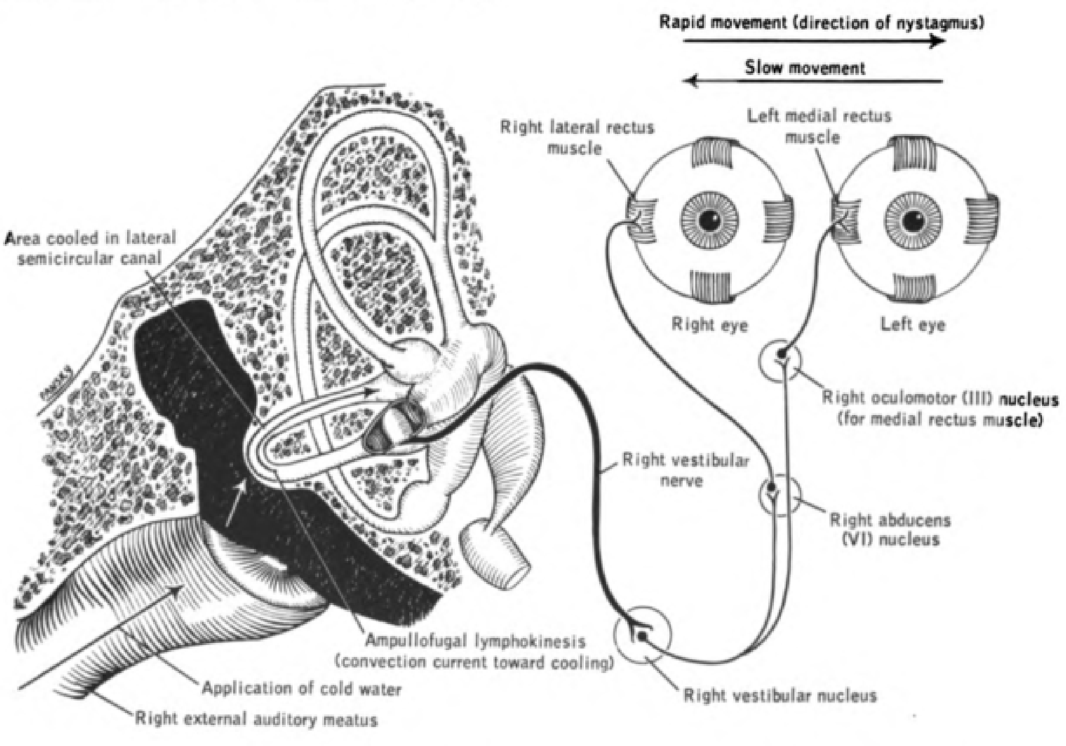


Image: "Caloric test. Cold water introduced into right external meatus showing effects opposite to that produced by introduction of hot water." by House, Earl Lawrence. Pansky, Ben. – A functional approach to neuroanatomy 1960. License: Public Domain

Nystagmus progressively increases for the next 40-60 seconds and then ebbs over the next few minutes. A rest period of a few minutes is reserved between 2 sequential irrigations. Eye movements are recorded and then the test results are interpreted as follows:

Test rationale

The direction of flow of the **endolymph** in the **semicircular canal** determines the polarity of the hair cells and their subsequent response. Thus, **endolymph flow towards the hair cells stimulates them, whereas flow away results in inhibition**.

On turning the head towards the right side, the endolymph moves to the right leading to stimulation of the right lateral semicircular canal and inhibition of the left semicircular canal.

The caloric reflex test is a measure of the **vestibulo-ocular reflex**. The vestibulo-ocular reflex is primarily designed to maintain **eye fixation in presence of head rotation**. Thus, when the head turns towards the right side, the vestibular system directs the eyes to move to the left to maintain fixation.

However, the vestibulo-ocular reflex is a primitive **brainstem response** and is normally inhibited by the cortex in a conscious patient. **Saccades,** or successions of discontinuous individual eye movements generated by the frontal cortex counteract the **tonic deviation response** of the vestibular system to continue fixation of a moving object.

The saccades determine the fast component of the nystagmus and the nystagmus is conventionally named for the direction of the fast component. This counter-regulatory mechanism is **lost in comatose patients with loss of cortical control**.

Thus, nystagmus to the right side is a combination of saccades to the right side and tonic deviation of the eyes towards the left side caused by hot water stimulation of the right ear in a conscious patient.

The interpretations of the caloric test in these myriad perspectives can be easily memorized as follows:

Level of consciousness	Test	Interpretation
Patient conscious	Hot water stimulation of the right ear	Right-sided nystagmus with a fast component to the right.
Patient unconscious	Hot water stimulation of the right ear	Patient comatose but not braindead: tonic deviation of the eyes to the left side.
		Patient comatose and brain dead: no deviation of eyes
Patient conscious	Cold water irrigation of the right ear	Left-sided nystagmus with a fast component to the left.

To simply remember: in conscious patient remember **COWS: Cold water leads to Opposite sided nystagmus and Warm Same side.**

In case of **vestibular dysfunction**, the anticipated nystagmus response would not be obtained.

The caloric reflex test is also a **marker of brainstem integrity**. It is a vital assessment tool in the battery of tests used to confirm brainstem functions before declaring a patient brain dead. The implications of this test in transplant medicine cannot be over-emphasized.

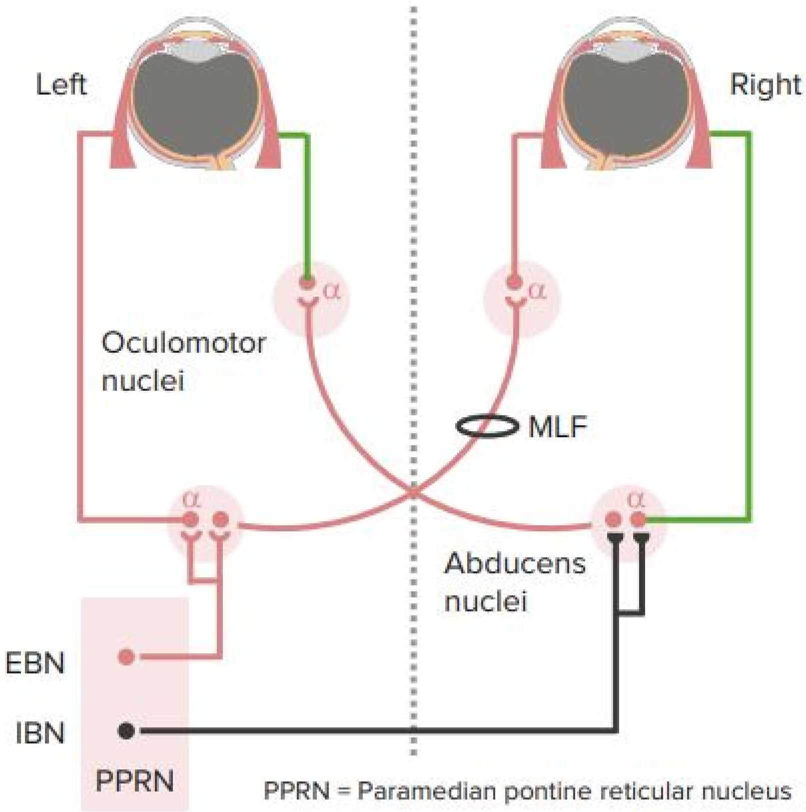
Control of Horizontal Gaze

There are 6 potential eye movements: saccadic, smooth pursuit, vergence, fixation, optokinetic and vestibulo-ocular reflex.

The **PPRF (pontine paramedian reticular formation)** is the center for the horizontal gaze. The supranuclear gaze centers function harmoniously and in a coordinated fashion to ensure macular fixation irrespective of movement of the object, head or the eyes.

The VI cranial nerve nucleus is the final common pathway for supranuclear horizontal gaze control.

The **frontal eye field (FEF)** generates contralateral saccades. Fibers from the FEF decussate and reach the contralateral PPRF. The PPRF signals the **ipsilateral VI cranial nerve nucleus**.



"Control of Horizontal Gaze" Image created by Lecturio

Simultaneous relay of information to the **contralateral III cranial nerve nucleus** takes place through the **medial longitudinal fasciculus (MLF)**.

Thus, stimulation of the left FEF signals the right PPRF, the right VI cranial nerve nucleus, the left III cranial nerve nucleus through the right MLF to cause **equal and instantaneous contraction** of the right lateral rectus and the left medial rectus to look on the right side.

This is in accordance with the **Hering law** of equal and reciprocal innervations to the paired "yoked" muscles.

A lesion of FEF causes unbalanced output from the other FEF. Thus, a right FEF lesion leads to left FEF unbalanced stimulation leading to right-sided eye deviation.

Lesion of the MLF causes **internuclear ophthalmoplegia**. A **medial pontine lesion** causes damage to the ipsilateral PPRF and the crossing MLF leading to “**One and a half syndrome”.**

Summary

The vestibular system conveys critical information instrumental in maintaining orientation and balance of the body.

The 3 semicircular canals – anterior, posterior and lateral – and the otolith organs – saccule and utricle – constitute the peripheral receptors of the vestibular system. The semicircular canals detect angular acceleration in the axis orthogonal to their orientation, while the otolith organs respond to gravity and linear acceleration.

In the caloric test, hot water stimulation of the ear in a conscious patient results in nystagmus directed to the same side. The caloric test is not only a measure of vestibular function but also of brainstem integrity.

The horizontal gaze is controlled by ipsilateral PPRF and contralateral FEF.

References

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Notes