# Basic Anatomy and Physiology of Peripheral Vestibular System

1. Consists of a boney labyrinth that contains 3 semicircular canals, cochlea, and a central chamber filled with perilymphatic fluid called the vestibule.[1]

2. The membranous vestibular labyrinth lies within the inner ear and contains:
    a. 3 semicircular canals (SCCs): anterior, posterior, and horizontal
    b. 2 otolith organs: utricle and saccule.

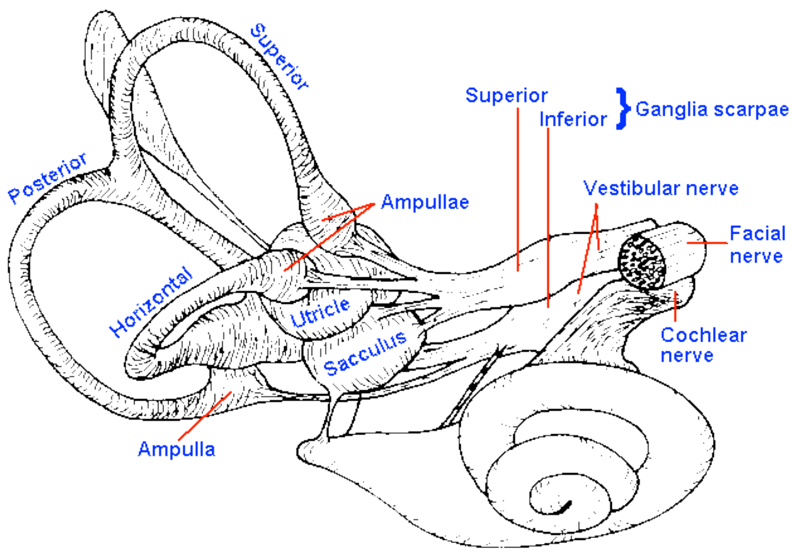


Figure 1.
From Mann, MD. Chapter 9: the Vestibular system, Figure 9-1: lateral view of right human labyrinth. Updated 2011 July. http://michaeldmann.net/mann9.html

3. The SCCs sense the velocity and direction of rotational movement of the head on the body around three axes, which are dependent on the 3 SCC's roughly perpendicular positioning to each other within the inner ear.[2] The horizontal canal tipped upwards~30 degrees.[2,3] [Figure 2]

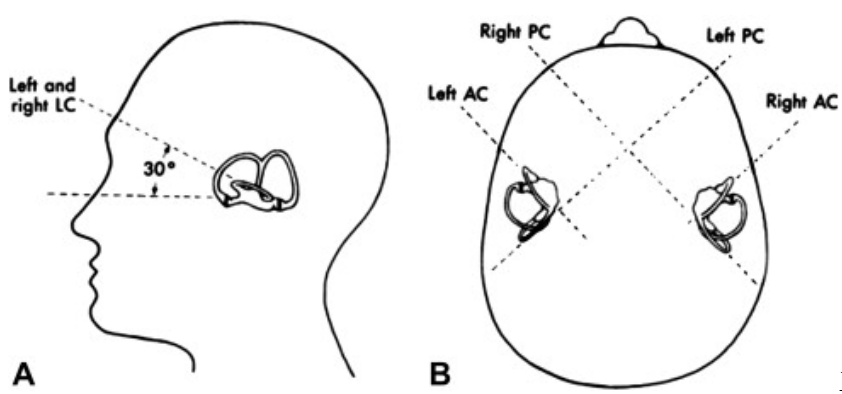


Figure 2.

From Kutz JW,Jr. The dizzy patient: Orientation of the semicircular canals in the head. Figure 1. *Med Clin North Am*. 2010;94:990.

    a. Each canal is paired with a contralateral coplanar mate that leads to a push-pull dynamic, meaning that during head movement, one side increases neuronal firing and other decreases firing which helps the body determine the direction of movement.[1,2]

b. The horizontal canals form a coplanar pair and detect rotational movements in horizontal plane, such as shaking head "no".[1]

c. The right anterior canal forms a pair with the left posterior canal, and the right posterior canal pairs with the left anterior canal. The anterior and posterior SCC's response to rotational movements in sagittal and frontal plane.[1,3]
    i. The majority of information during static stance, walking and running occurs in sagittal plane and therefore is sensed by anterior and posterior SCCs.[1]

d. Each SCC is filled with endolymph fluid and has enlargement at one end called the ampula. The ampula houses the crista ampullaris, which contains the hair cells that facilitate the transduction of rotational motion into neural activity.[2] [Figure 3]

    i. Hair cells project up from the crista ampullaris into the cupula, a gelatinous material within the ampulla.[2]
    ii. Hair cells have small projections called kinocilia and sterocilia.
    iii. Each hair cell is innervated by afferent neuron located in vestibular (Scarpa's) ganglion.[2]
    iv. With head movement, the movement of the endolymph fluid displaces the cupula moving the kinocilium and sterocilia away from direction of head motion, which depolarizes the hair cells and increases neuronal activity to the vestibular ganglion and cranial nerve VIII (vestibulocochlear).[1,2]

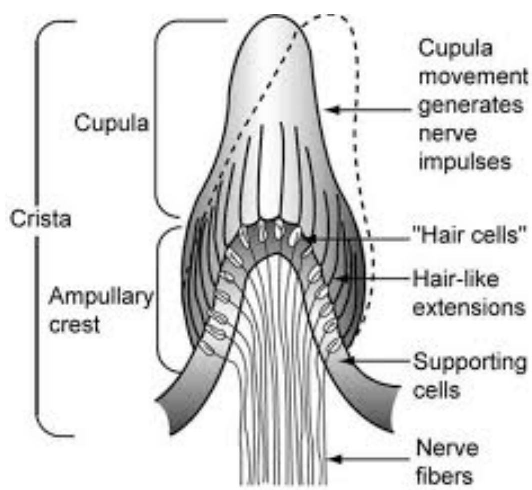


Figure 3.

From Coulter GR, Vogt GL. Effects of space flight on human vestibular system. Figure 4: Crista. *http://weboflife.nasa.gov/learningResources/vestibularbrief.htm*

e. Angular movement is detected by comparing input from coplanar SCC mates.[2] When the head rotates to the right, hair cells on right SCC are excited and hair cells on left SCC are inhibited.

4. The two otolith organs (saccule and utricle) lie in medial vestibule and sense linear accelerations of the head and static head orientation in respect to gravity.[1,2] These movements occur around standard X, Y, Z axes.
    a. Saccule: senses movement in the sagittal plane, vertical linear acceleration. e.g. head translation during deep knee bends.[1]
    b. Utricle- senses motion in horizontal plane, horizontal linear acceleration. e.g. head translation during forward walking.[1]

c. Saccule and Utricle contain macula, the sensory epithelium that contains hair cells and supporting cells. [Figure 4]

d. The hair cells project up into a gelatinous material that is covered by a fibrous otolithic membrane that contains otoconia.[2] Otoconia are calcium carbonate crystals that provide otolithic membrane with inertial mass, thereby making it heavier than surrounding structures.[2]

    i. During head motion, there is a shearing motion between the heavier otolithic membrane and macula, which displaces the hair cells and generates action potentials through CN VIII.[2]
        1. The utricular hair cells are excited during horizontal linear acceleration or static head tilt.[2]
        2. The saccular hair cells are excited during vertical linear acceleration. [2]

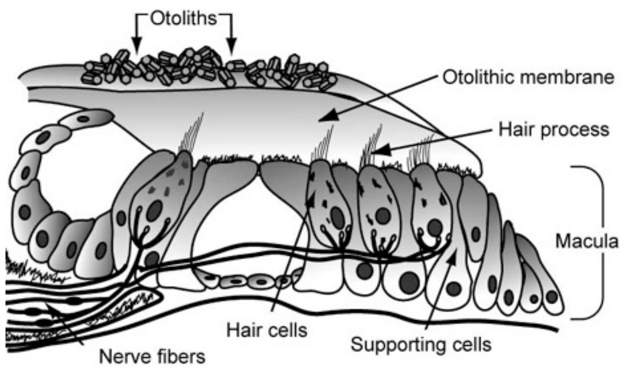


Figure 4.
From Coulter GR, Vogt GL. Effects of space flight on human vestibular system. Figure 6: Otolith organ (saccule or utricle) *http://weboflife.nasa.gov/learningResources/vestibularbrief.htm*

**5. Processing of Vestibular information**

a. There is a tonic firing (90 pulses per second) at rest that is symmetrical between bilateral vestibular nerves (CN VIII).[4] During head movement, the firing increases on the side of direction of movement and decreases on opposite side leading to a asymmetry of neural activity (push-pull mechanism).[2,4] This asymmetric activity is transported to the vestibular nuclei where it is interpreted as head movement by the CNS.[4] If pathology causes asymmetry, the CNS will interpret this as head movement, when none is occurring.

b. When head movement occurs, action potentials generated from the SCCs and otolith organs are sent to the Scarpa's vestibular ganglion (of CN VIII) located within the internal auditory canal.[1]

c. From here vestibular superior and inferior division vestibular nerve (CN VIII) fibers transmit afferent signals from bilateral labyrinths through the internal auditory canal and temporal bone to the posterior fossa where they enter the brainstem at the pontomedullary junction.[1]

d. This peripheral input is then sent to vestibular nucleus complex (in medulla) and cerebellum.[1]
    i. 4 Vestibular nuclei on opposite sides of the brainstem communicate through commissures, which allows interpretation of push-pull paring (increase or decrease of tonic firing rate) generated by SCC and otolith pairs.[1]
    ii. The cerebellum's role is to monitor and adjust vestibular signals.[1]

e. Peripheral vestibular information from labyrinths received by the vestibular nuclei is processed with somatosensory and visual information from the cerebellum, ocular motor nuclei, and brainstem reticular systems.[1] These other sensory processing systems help adjust and influence the responses and perception to head movement and become essential in vestibular hypofunction recovery.[1]

f. Processing of all information together results in appropriate efferent signals to Vestibulo-ocular Reflex (VOR), Vestibulo-spinal Reflex (VSR), Vestibulo-collic Reflex (VCR) and extraocular and skeletal muscles.[1]

## 6. Physiology of Vestibulo-ocular reflex (VOR)

a. The SCCs provide input about head velocity, which allows the VOR to generate matched eye movement that that maintains focus on objects during fast head movements (e.g. during walking, running and most ADLs).[1,3]

b. The VOR gain is the ratio of eye to head movement amplitude.[1] Ideally it is 1.[1,3]

c. Information from SCC travels through second-order neurons from vestibular nuclei ipsilaterally and contralaterally through the medial longitundinal fasciculus to innervate ocular muscles that cause VOR.[3]

d. For instance, with rotation to the left, excitatory inputs from the left lateral SSC detects rotation to the left and excites neurons in left vestibular nucleus causing reflexive eye movements to the right. This allows the eyes to stay fixated on a visual target with head movement.

e. Details of horizontal VOR process described below.[1] [Figure 5]
   i. Excitatory fibers from left medial vestibular nucleus cross and innervate the contralateral (right) abducens nucleus. This causes contraction of the right lateral rectus muscle.
      1. From the abducens nucleus, excitatory fibers cross midline and ascend to excite the left oculomotor nucleus that contracting the left medial rectus.
   ii. Inhibitory fibers from right medial vestibular nucleus cross and ascend to contralateral (left) abducens to inhibit activity and cause relaxation of left lateral rectus.
      1. From the left abducens, inhibitory fibers cross midline and ascend to inhibit the right oculomotor nucleus that relaxes the right medial rectus.

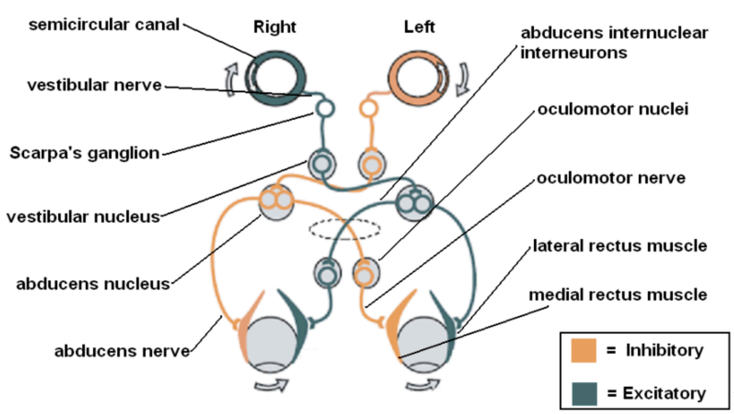

Figure 5.

From Wikimedia commons and Haggstrom M. Oct 2007. Vestibular Ocular Reflex. http://en.wikipedia.org/wiki/File:Vestibulo-ocular_reflex.PNG

f. Similarly, excitation of the anterior SSC by pitching head down, causes upward elevation of eyes and excitation of posterior SSC by pitching head up causes downward deviation of both eyes.[3] This helps maintain visual fixation during higher velocity head movements.
g. During low velocity head movements (<2 Hz) smooth pursuit is able to maintain focus using information from visual cortex sent o vestibular nucleus complex.[3]

**References**


1. Herdman SJ. Vestibular Rehabilitation. 3rd ed. Philadelphia, PA: F.A. Davis Company; 2007:2-309.

2. Schubert MC, Minor LB. Vestibulo-ocular physiology underlying vestibular hypofunction. *Physical Therapy.* 2004;84(4):373-382.

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