# Vestibular Function and Anatomy

UTMB Grand Rounds

April 14, 2004

Gordon Shields, MD

Arun Gadre, MD

- System of balance
- Membranous and bony labyrinth embedded in petrous bone
- 5 distinct end organs
  - 3 semicircular canals: superior, lateral, posterior
  - 2 otolith organs: utricle and saccule

- Semicircular canals sense angular acceleration
- Otolithic organs (utricle and saccule) sense linear acceleration

# Embryology

- 3rd week of embryonic development
- Otic placode formed from neuroectoderm and ectoderm
- Otocyst or otic vesicle 4th week

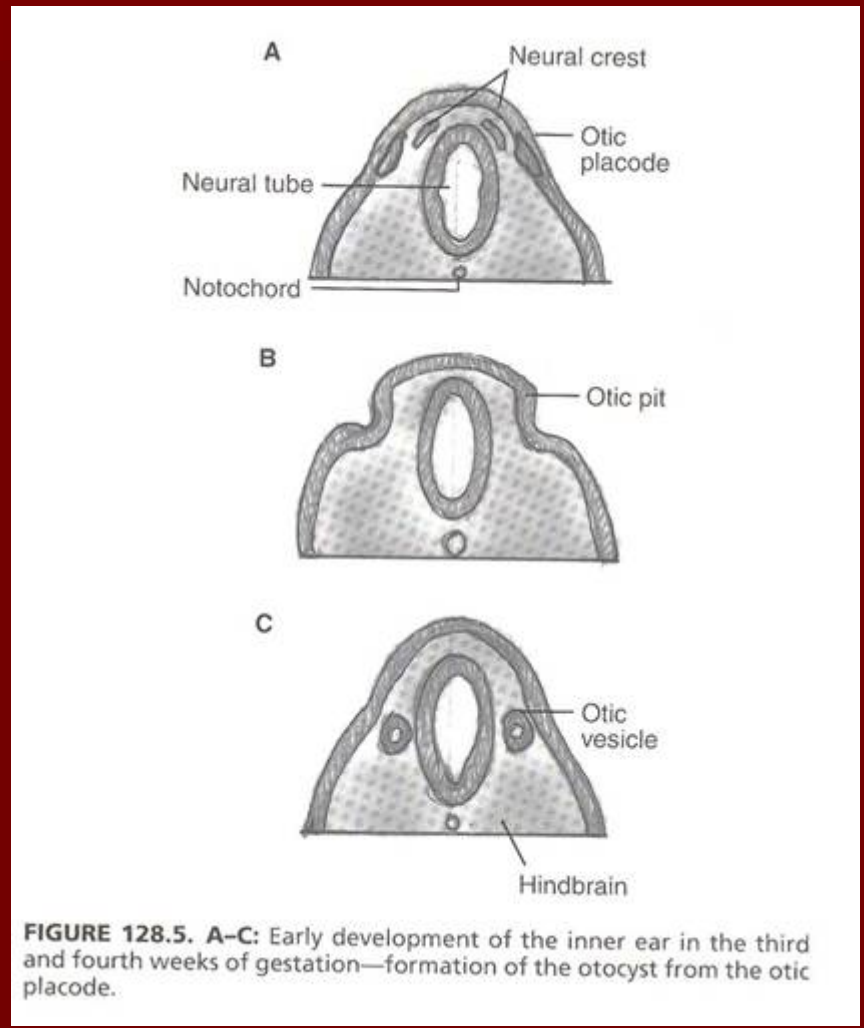



**FIGURE 128.5. A–C:** Early development of the inner ear in the third and fourth weeks of gestation—formation of the otocyst from the otic placode.

# Embryology

- Endolymphatic duct forms
- Utricular chamber becomes utricle/semicircular canals
- Saccular chamber becomes saccule/cochlea
- Separation of saccule and cochlea-ductus reuniens

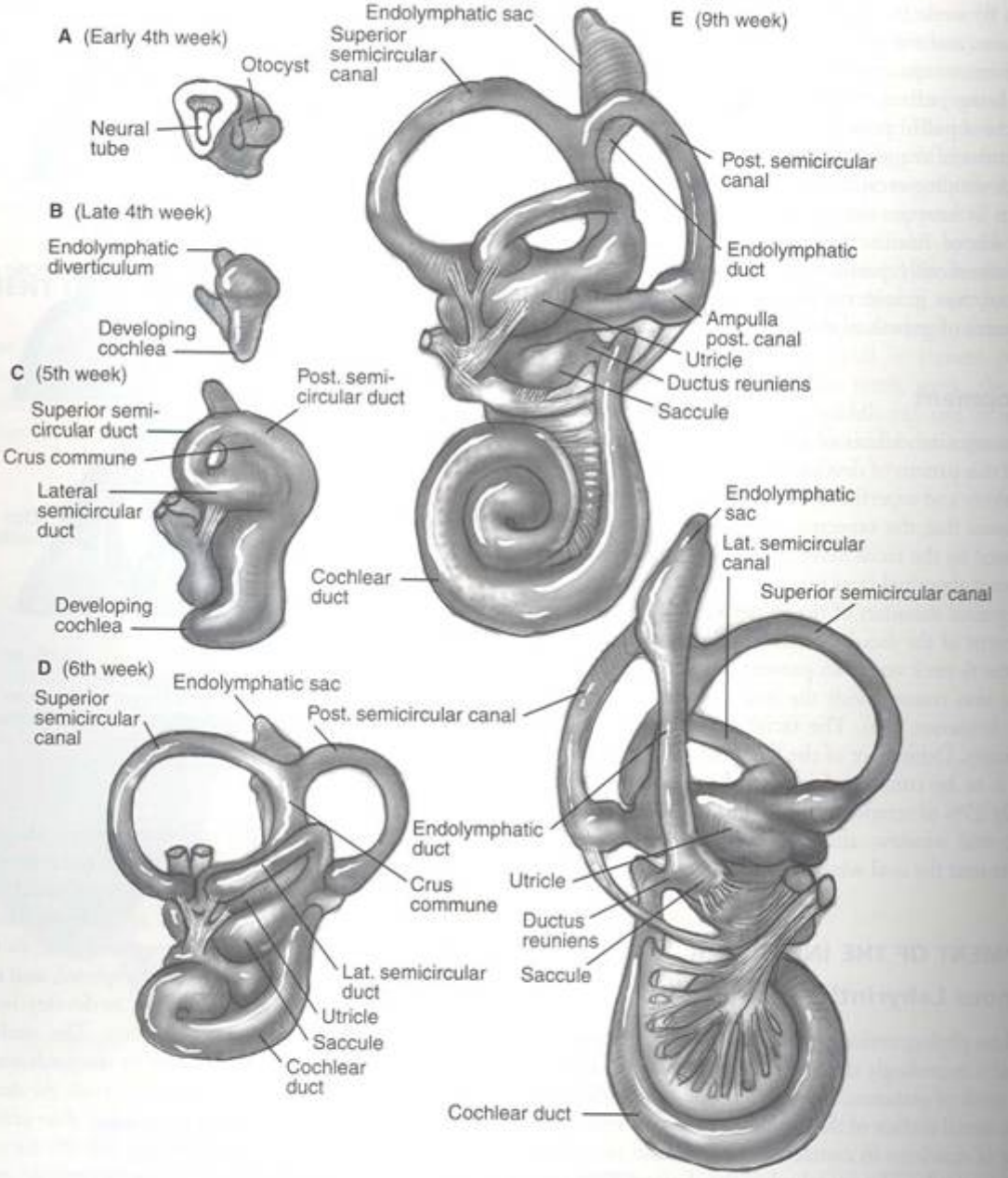



**FIGURE 128.6. A–D:** Development of the membranous labyrinth from gestational weeks 4 through 9.

# Embryology

- Week 3 sensory epithelia develop from ectoderm
- 3 cristae, 2 maculae
- Vestibulocochlear ganglion starts as one then spits into superior and inferior divisions
  - Superior division: Superior/lateral canals, utricle
  - Inferior division: saccule, posterior canal (via singular nerve)

- Semicircular canals are orthogonal to each other
- Lateral canal inclined to 30 degrees
- Superior/postereor canals 45 degrees off of sagittal plane

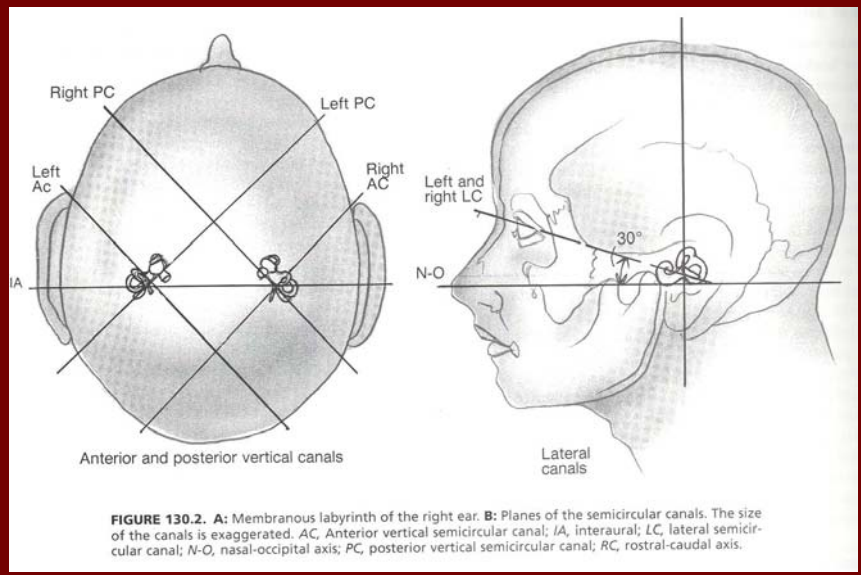



**FIGURE 130.2. A:** Membranous labyrinth of the right ear. **B:** Planes of the semicircular canals. The size of the canals is exaggerated. *AC,* Anterior vertical semicircular canal; *IA,* interaural; *LC,* lateral semicircular canal; *N-O,* nasal-occipital axis; *PC,* posterior vertical semicircular canal; *RC,* rostral-caudal axis.

- Utricle is in horizontal plane
- Saccule is in vertical plane

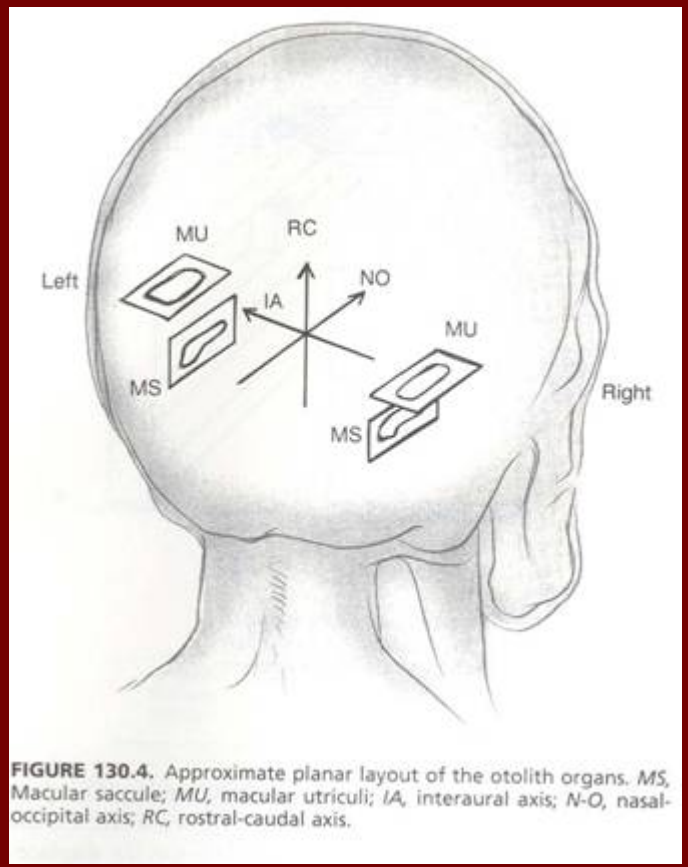



**FIGURE 130.4.** Approximate planar layout of the otolith organs. *MS,* Macular saccule; *MU,* macular utriculi; *IA,* interaural axis; *N-O,* nasal-occipital axis; *RC,* rostral-caudal axis.

# Anatomy

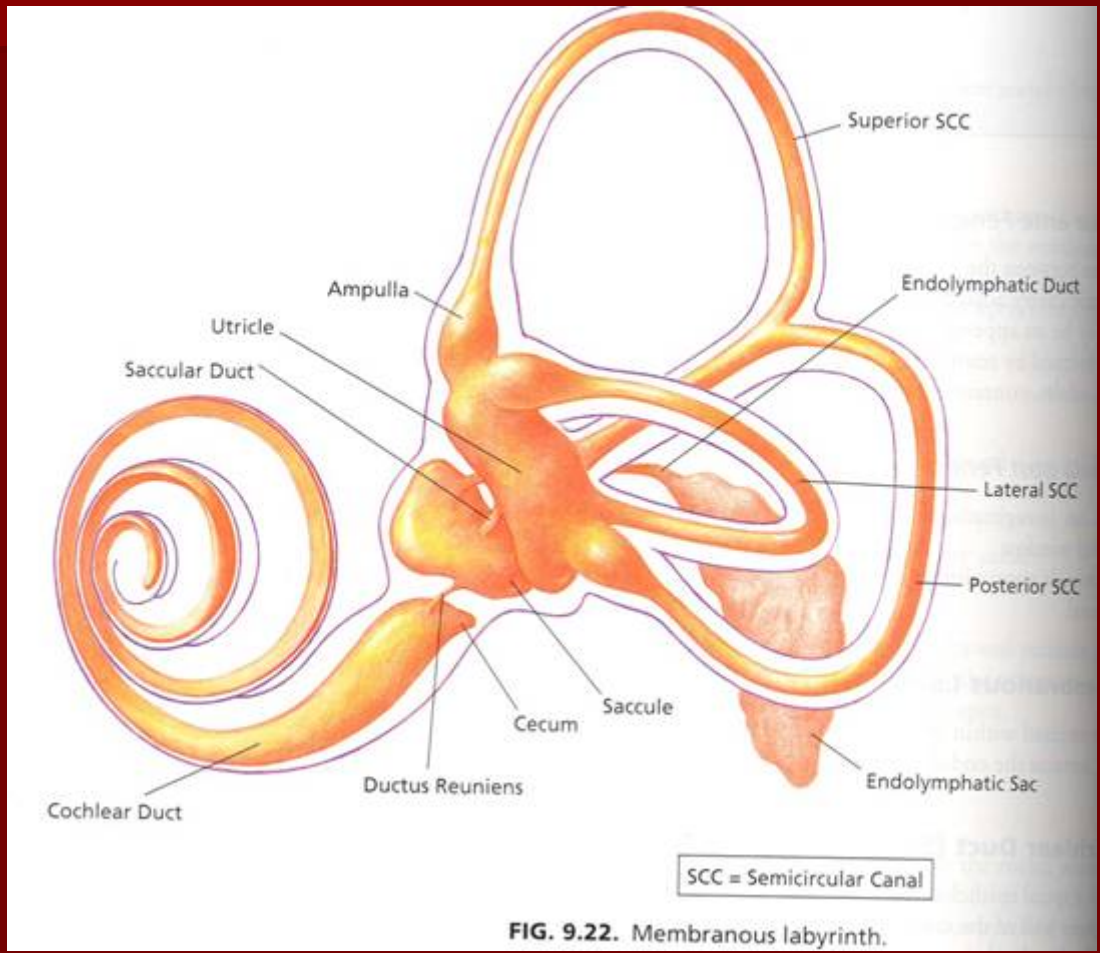



**FIG. 9.22.** Membranous labyrinth.

- There are five openings into area of utricle
- Saccule in spherical recess
- Utricle in elliptical recess

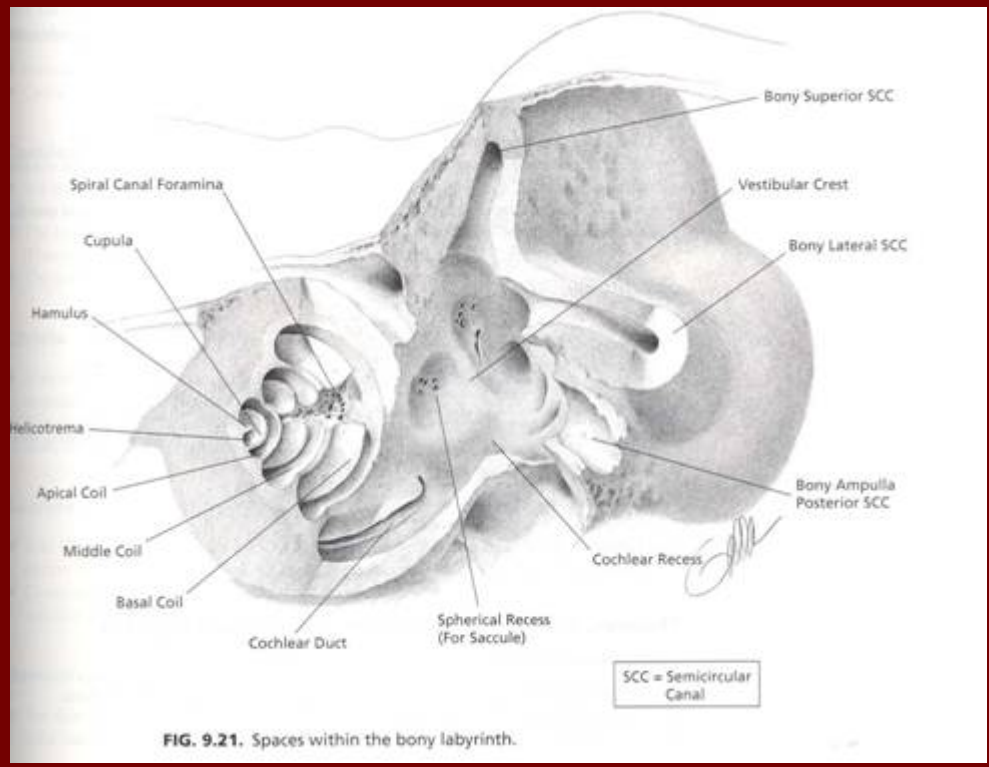


FIG. 9.21. Spaces within the bony labyrinth.

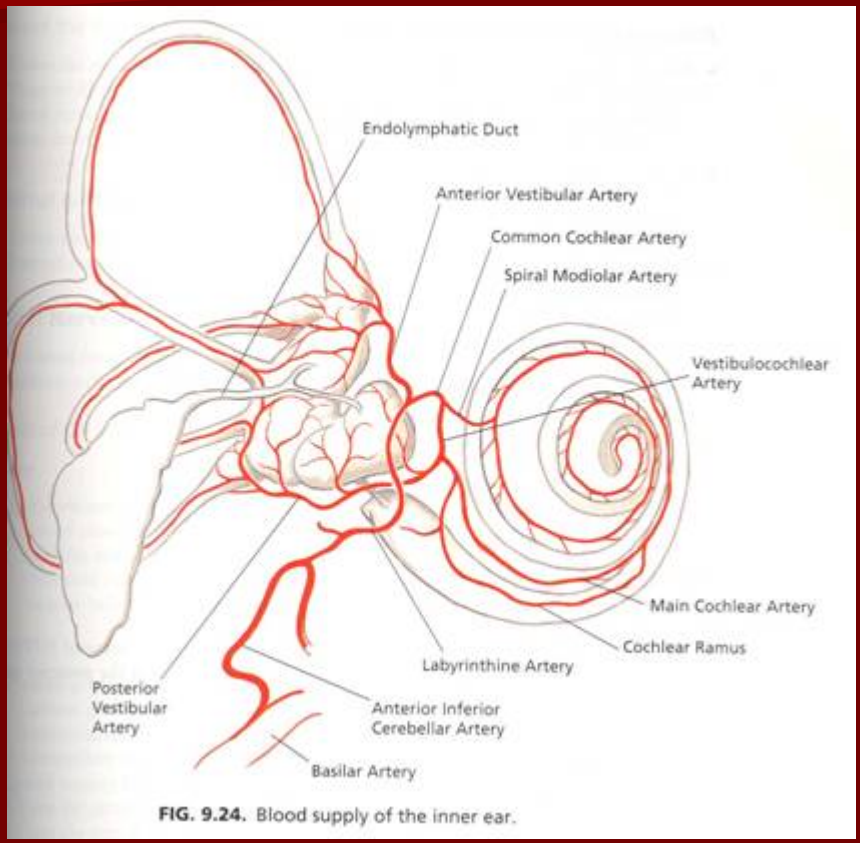


FIG. 9.24. Blood supply of the inner ear.

- 45% from AICA
- 24% superior cerebellar artery
- 16% basilar
- Two divisions: anterior vestibular and common cochlear artery

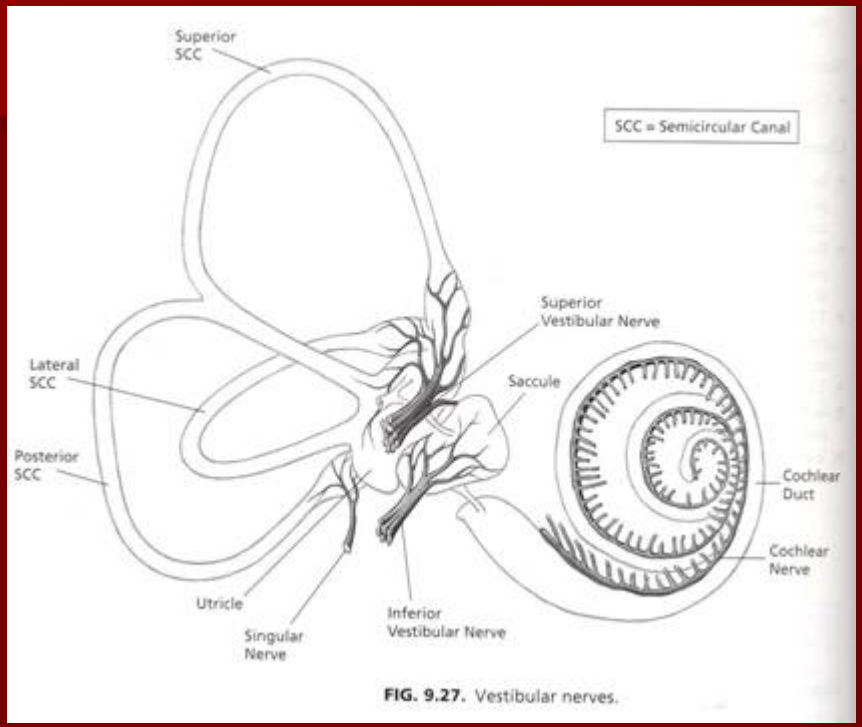


FIG. 9.27. Vestibular nerves.

- Superior vestibular nerve: superior canal, lateral canal, utricle
- Inferior vestibular nerve: posterior canal and saccule

- Membranous labyrinth is surrounded by perilymph
- Endolymph fills the vestibular end organs along with the cochlea

- Perilymph
  - Similar to extracellular fluid
  - $K^+ = 10mEQ$, $Na^+ = 140mEq/L$
  - Unclear whether this is ultrafiltrate of CSF or blood
  - Drains via venules and middle ear mucosa

- Endolymph
  - Similar to intracellular fluid
  - $K^+$=144mEq/L, $Na^+$=5mEq/L
  - Produced by marginal cells in stria vascularis from perilymph at the cochlea and from dark cells in the cristae and maculae
  - Absorbed in endolymphatic sac which connected by endolymphatic, utricular and saccular ducts

# Sensory structures

- Ampulla of the semicircular canals
- Dilated end of canal
- Contains sensory neuroepithelium, cupula, supporting cells

- Cupula is gelatinous mass extending across at right angle
- Extends completely across, not responsive to gravity
- Crista ampullaris is made up of sensory hair cells and supporting cells

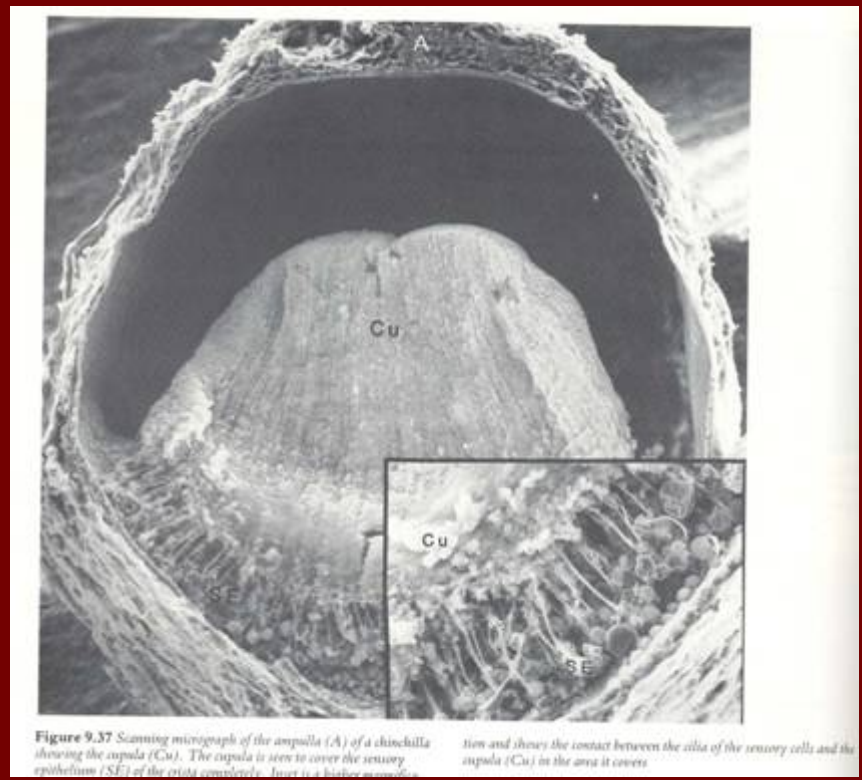



**Figure 9.37** *Scanning micrograph of the ampulla (A) of a chinchilla showing the cupula (Cu). The cupula is seen to cover the sensory epithelium (SE) of the crista completely. Inset is a higher magnification and shows the contact between the cilia of the sensory cells and the cupula (Cu) in the area it covers.*

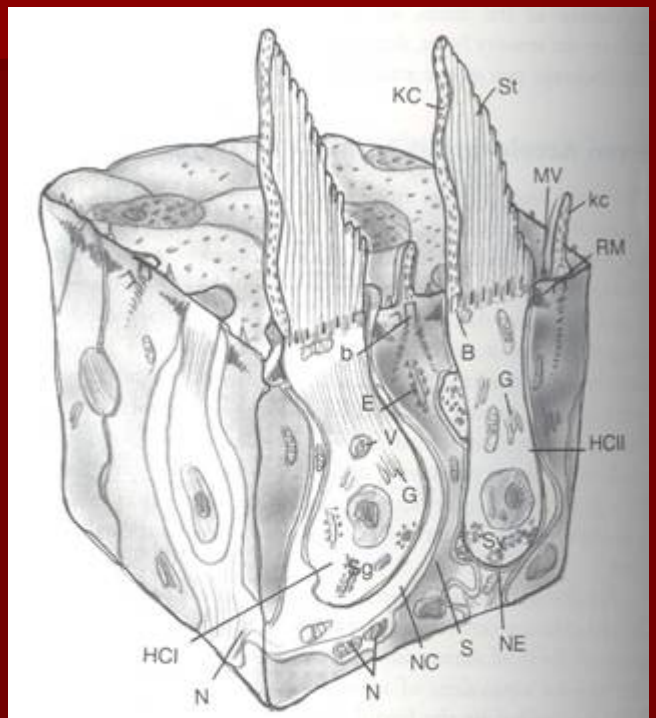
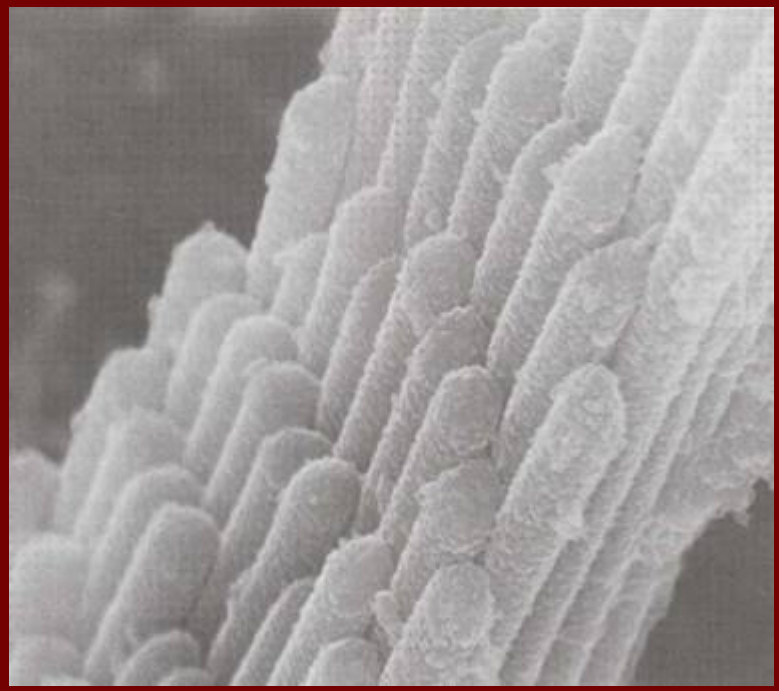



**FIGURE 130.5.** Vestibular sensory epithelium and its innervation. *HCI, HCII,* Types of hair cells; *St,* stereocilia; *KC,* kinocilia (*kc,* modified kinocilia and roots [*b*] of supporting cells, [*S*]); *N,* nerve fiber; *NC,* nerve chalice; *NE,* nerve endings; *Sy,* synaptic structures (*G,* Golgi membranes; *RM,* multivesicular reticular membrane; *E,* endoplasmic reticulum; *MV,* microvilli; *V,* vesicle). (Modified from Spoendlin HH. The ultrastructure of the vestibular sense organ. In: Wolfson RJ, ed. *The vestibular system and its diseases.* Philadelphia: University of Pennsylvania Press, 1966: 39, with permission.)

- Sensory cells are either Type I or Type II
- Type I cells are flask shaped and have chalice shaped calyx ending
- One chalice may synapse with 2-4 Type I cells
- Type II cells – cylinder shaped, multiple efferent and afferent boutons


Hair cells have 50-100 stereocilia and a single kinocilium.



stereocilia are not true cilia, they are graded in height with tallest nearest the kinocilium.

- Kinocilium is located on one end of cell giving each cell a polarity
- Has 9+2 arrangement of microtubule doublets
- Lacks inner dynein arms, and central portion of microtubules not present near ends – may mean they are immobile or weakly mobile

- Each afferent neuron has a baseline firing rate
- Deflection of stereocilia toward kinocilium results in an increase in the firing rate of the afferent neuron
- Deflection away causes a decrease in the firing rate

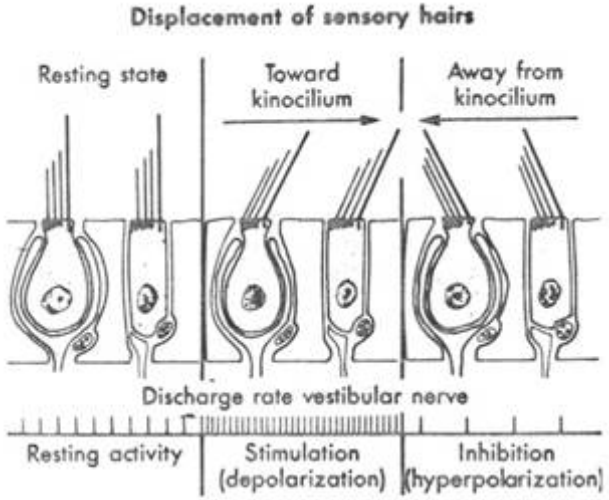
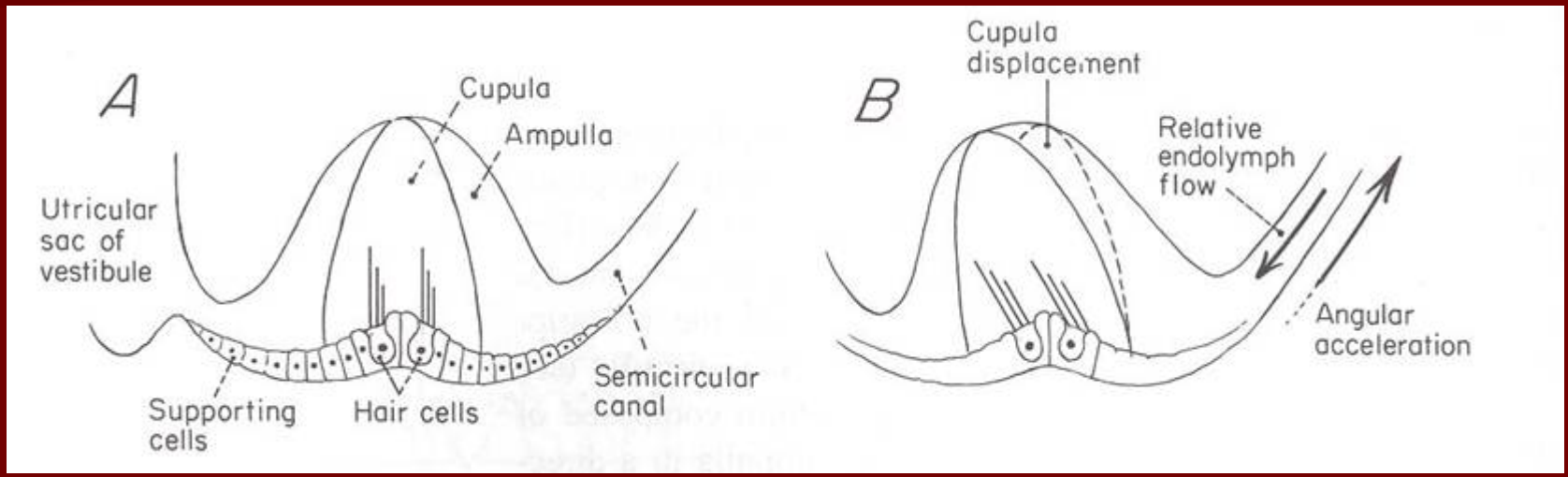



Fig. 8. Discharge rate of vestibular nerve fibers at rest and as a function of displacement of stereocilia (sensory hairs) relative to kinocilium. (From Wersall J and Lundquist P-G. In: Graybiel A. Second symposium on the role of vestibular organs in space exploration, NASA SP115. Washington, DC, US Government Printing Office.)


A
Cupula
Ampulla
Utricular sac of vestibule
Supporting cells
Hair cells
Semicircular canal
B
Cupula displacement
Relative endolymph flow
Angular acceleration

- kinocilia are located closest to utricle in lateral canals and are on canalicular side in other canals
- Ampullopetal flow (toward the ampulla) excitatory in lateral canals, inhibitory in superior/posterior canals
- Ampullofugal flow (away from the ampulla) has opposite effect

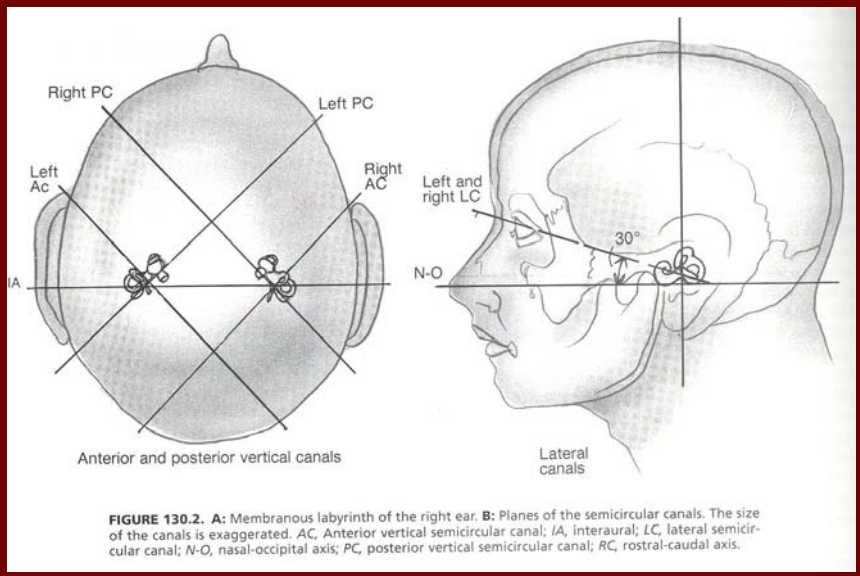
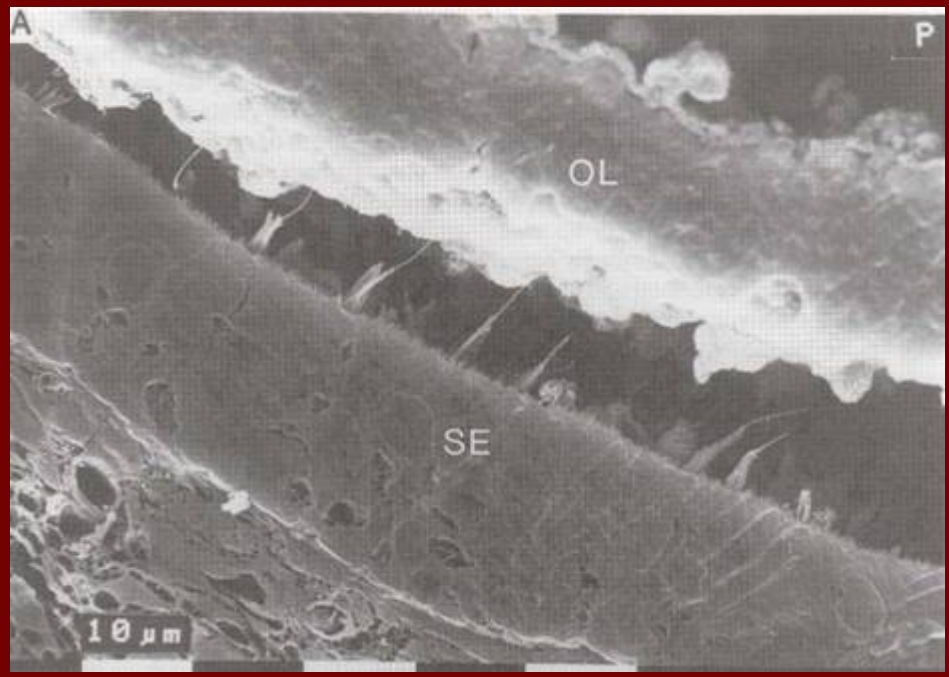



**FIGURE 130.2. A:** Membranous labyrinth of the right ear. **B:** Planes of the semicircular canals. The size of the canals is exaggerated. *AC,* Anterior vertical semicircular canal; *IA,* interaural; *LC,* lateral semicircular canal; *N-O,* nasal-occipital axis; *PC,* posterior vertical semicircular canal; *RC,* rostral-caudal axis.

- Semicircular canals are paired
  - Horizontal canals
  - Right superior/left posterior
  - Left superior/right posterior
  - Allow redundant reception of movement
  - Explains compensation after unilateral vestibular loss

# Otolithic organs

- Utricle and saccule sense linear acceleration
- Cilia from hair cells are embedded in gelatinous layer
- Otoliths or otoconia are on upper surface


A
P
OL
SE
10 µm

- Calcium carbonate or calcite
- 0.5-30um
- Specific gravity of otolithic membrane is 2.71-2.94
- Central region of otolithic membrane is called the striola

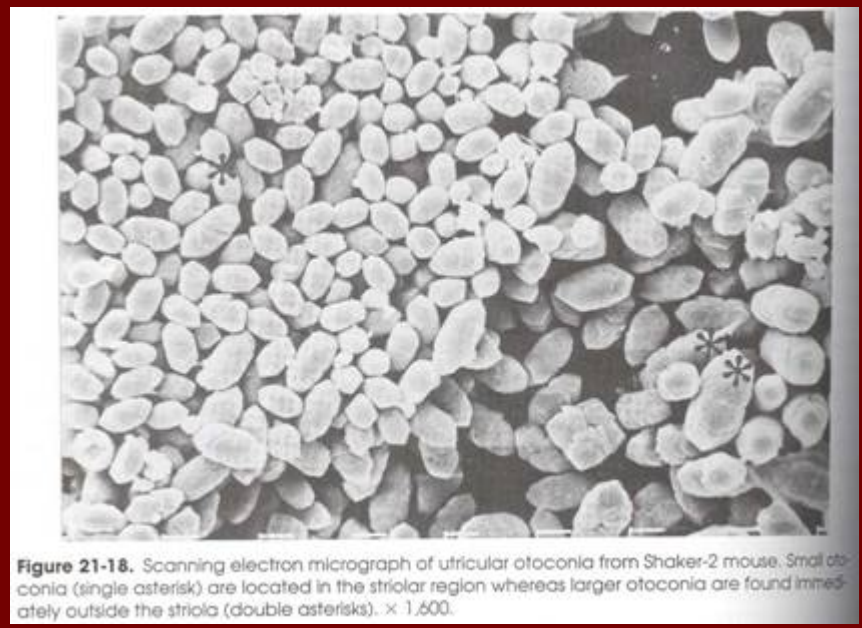


**Figure 21-18.** Scanning electron micrograph of utricular otoconia from Shaker-2 mouse. Small otoconia (single asterisk) are located in the striolar region whereas larger otoconia are found immediately outside the striola (double asterisks). × 1,600.

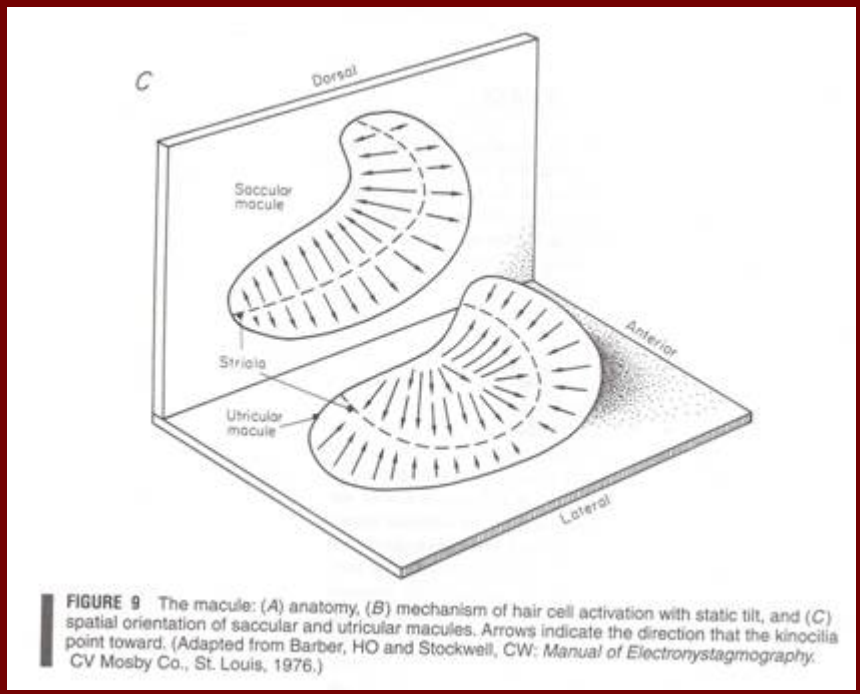
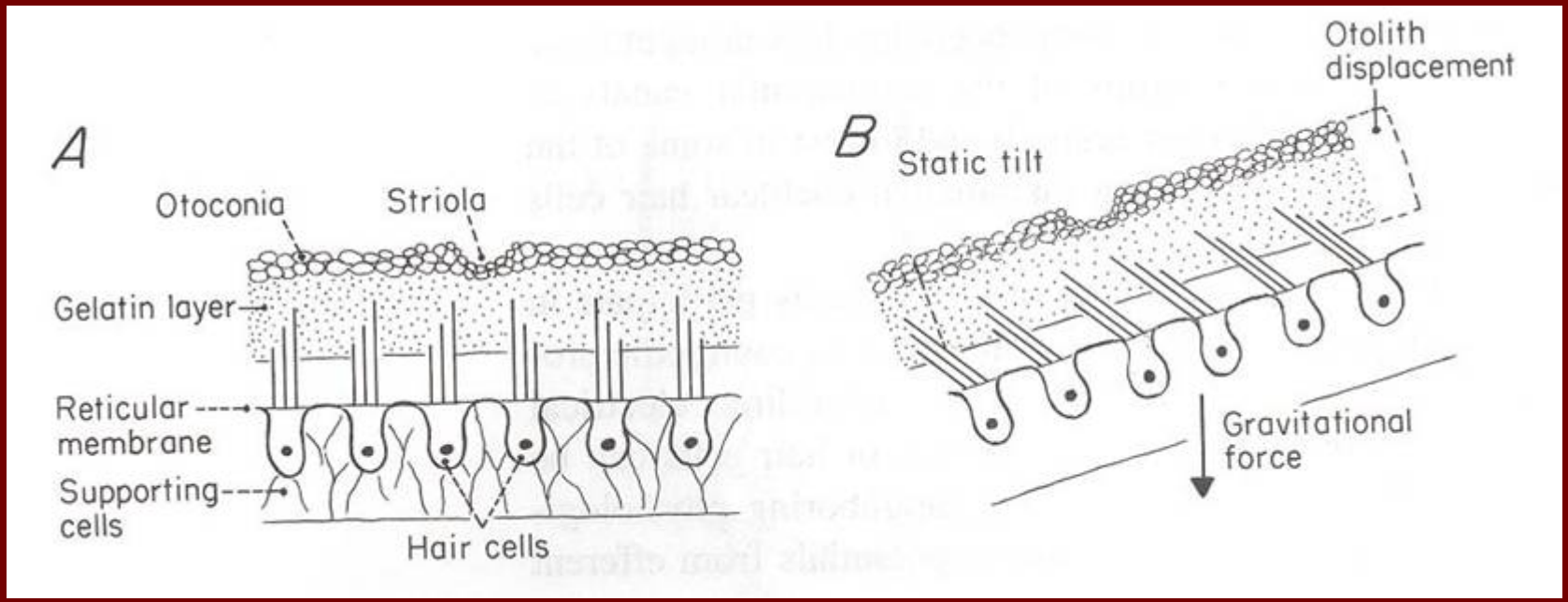



FIGURE 9 The macule: (*A*) anatomy, (*B*) mechanism of hair cell activation with static tilt, and (*C*) spatial orientation of saccular and utricular macules. Arrows indicate the direction that the kinocilia point toward. (Adapted from Barber, HO and Stockwell, CW: *Manual of Electronystagmography.* CV Mosby Co., St. Louis, 1976.)

- Saccule has hair cells oriented away from the striola
- Utricle has hair cells oriented towards the striola
- Striola is curved so otolithic organs are sensitive to linear motion in multiple trajectories


A
Otoconia
Striola
Gelatin layer
Reticular membrane
Supporting cells
Hair cells
B
Static tilt
Otolith displacement
Gravitational force

# Central connections

- Scarpa’s ganglion is in the internal auditory canal
- Contains bipolar ganglion cells of first order neurons
- Superior and inferior divisions form common bundle which enters brainstem
- No primary vestibular afferents cross the midline

- Afferent fibers terminate in the vestibular nuclei in floor of fourth ventricle
  - Superior vestibular nucleus
  - Lateral vestibular nucleus
  - Medial vestibular nucleus
  - Descending vestibular nucleus

- Vestibular nuclei project to
  - Cerebellum
  - Extraocular nuclei
  - Spinal cord
  - Contralateral vestibular nuclei

- Senses and controls motion
- Information is combined with that from visual system and proprioceptive system
- Maintains balance and compensates for effects of head motion

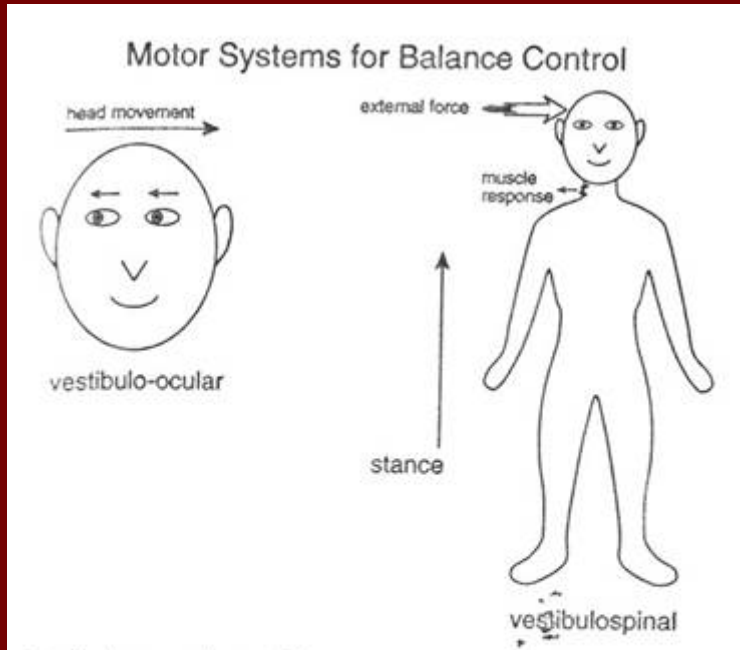



Fig. 7. An overview of the motor systems that are responsible for control of vestibular reflexes. Movements of the eye constitute the motor output of vestibulo-ocular reflexes. Movements and muscle tone of the neck, trunk, and lower extremities mediate vestibulospinal reflexes. These reflexes act to oppose effects of external forces and maintain stance (body orientation in relation to gravity).

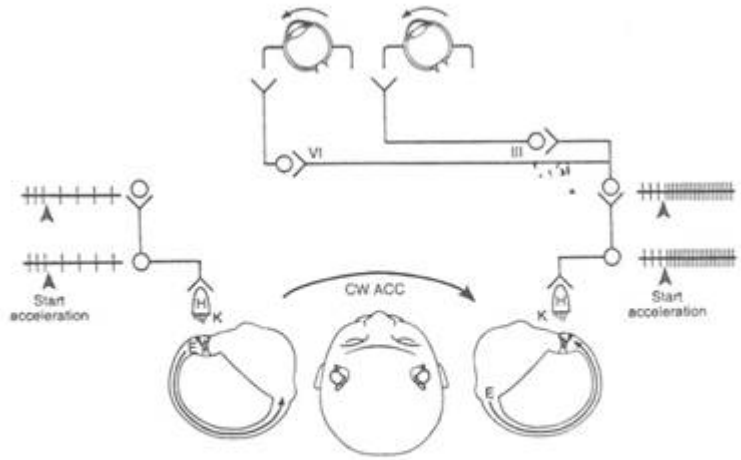



**Figure 1.** The functioning of the horizontal semicircular canals under the condition of angular acceleration (ACC) in the clockwise (CW) direction. Indications of firing rate changes on the primary afferent nerve fibers and at the level of the vestibular nuclei are given in the spike trains in the right and left sides of the figure. E = endolymph; K = kinocilium; H = hair cell of the lateral crista; III = oculomotor nerve, cranial nerve III; VI = abducens nerve, cranial nerve VI. (*From* Shepard NT, Telian SA: Practical Management of the Balance Disorder Patient. San Diego, Singular Publishing Group, 1996, p 5; with permission.)

- Vestibulo-ocular reflex
  - Membranous labyrinth moves with head motion
  - Endolymph does not causing relative motion
  - Cupula on right canal deflected towards utricle causing increase in firing rate, left deflects away causing a decrease in firing rate.
  - Reflex causes movement of eyes to the left with saccades to right
  - Stabilizes visual image

- If acceleration stops, and spin to right is at constant velocity, sensation of motion stops after 14-20 seconds as does nystagmus
- Cupula only takes 8-10 seconds to return to equilibrium position
- Vestibular integrator is the term for the prolongation and is mediated by the vestibular nuclei and cerebellum

# Vestibulospinal Reflex

- Senses head movement and head relative to gravity
- Projects to antigravity muscles via 3 major pathways:
  - Lateral vestibulospinal tract
  - Medial vestibulospinal tract
  - Reticulospinal tract

# How do calorics work?

- Patient is lying down with horizontal canals oriented vertically (ampulla up)
- Cold water irrigation causes endolymph in lateral portion to become dense and fall causing deflection of cupula away from utricle with a decrease in the firing rate
- This causes nystagmus with fast phase (beat) away from the stimulus

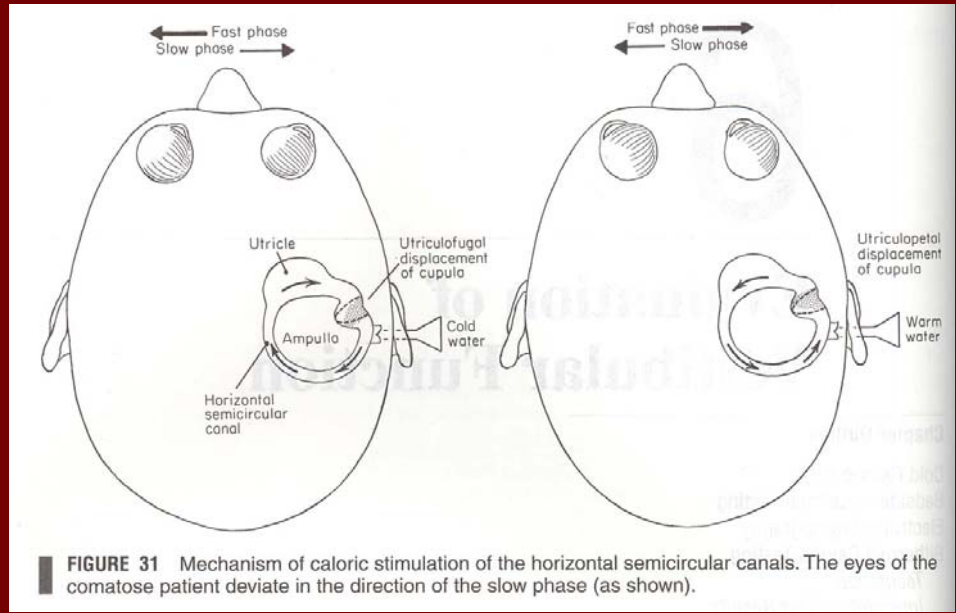



**FIGURE 31** Mechanism of caloric stimulation of the horizontal semicircular canals. The eyes of the comatose patient deviate in the direction of the slow phase (as shown).

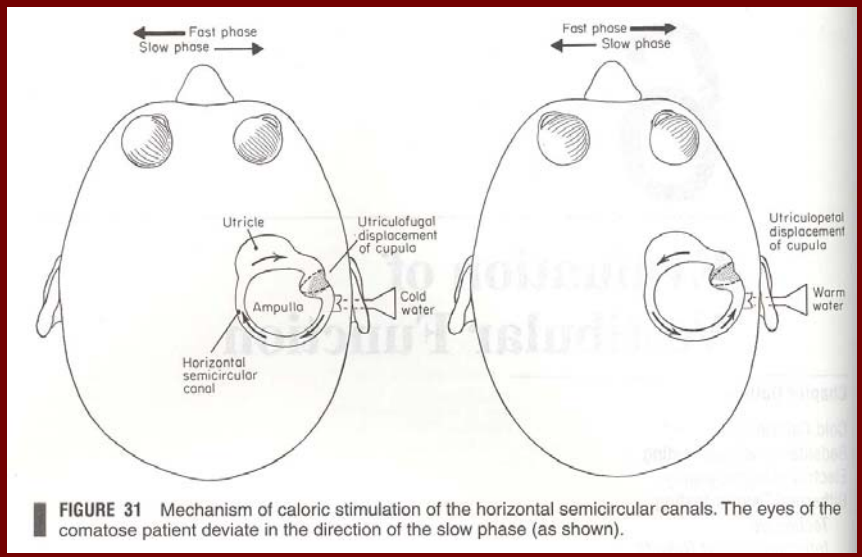



**FIGURE 31** Mechanism of caloric stimulation of the horizontal semicircular canals. The eyes of the comatose patient deviate in the direction of the slow phase (as shown).

- With warm water irrigation column of endolymph becomes less dense, rises and causes deflection of cupula toward the utricle
- Results in increase firing rate and nystagmus which beats towards the stimulation
- COWS (cold opposite, warm same)

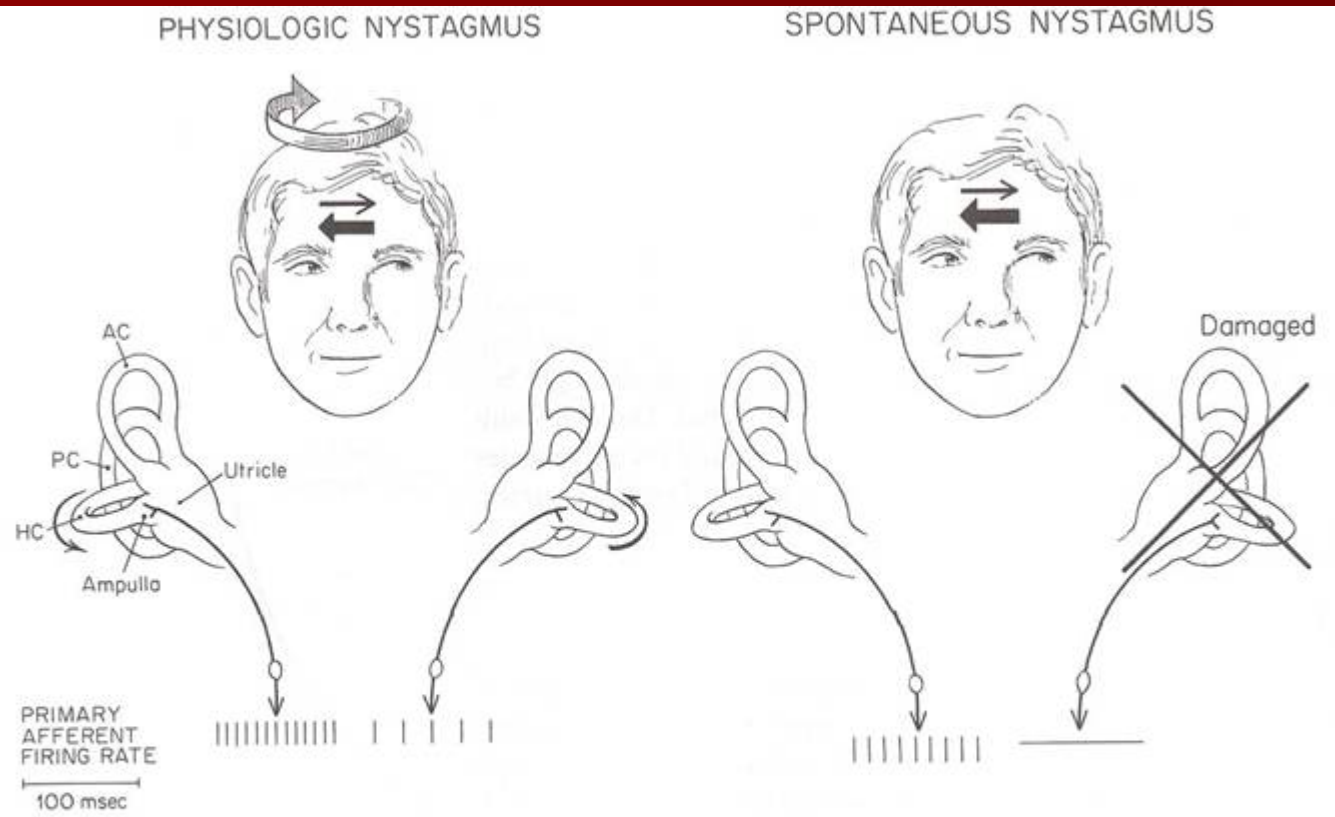



**FIGURE 16** Primary afferent nerve activity associated with rotation-induced physiological nystagmus and spontaneous nystagmus resulting from a lesion of one labyrinth. The thin straight arrows indicate the direction of slow components; the thick straight arrows indicate the direction of fast components; curved arrows show the direction of endolymph flow in the horizontal semicircular canals. AC = anterior canal, PC = posterior canal, HC = horizontal canal.

# Sources


Shepard NT, Solomon D. Functional Operation of the Balance System in Daily Activities. *Otolaryngologic Clinics of North America* 2000;33(3):455-468.

Minor LB. Physiological principles of vestibular function on earth and in space. *Otolaryngology-Head and Neck Surgery* 1998;118(3 part 2):S5-S15.

Abdel Razek OA. Anatomy of the Vestibular System. www.emedicine.com

Hoffman R, Strunk C. Vestibular Anatomy and Physiology. Department of Otolaryngology Grand Rounds University of Texas Medical Branch December 9, 1992.

Baloh RW. *Dizziness, Hearing Loss, and Tinnitus*. Philadephia, F.A. Davis Company, 1998.

Jahn AF, Santos-Sacchi J. *Physiology of the Ear*. Second edition. San Diego, Singular, 2001.

Friedman I, Ballantyne J. *Ultrastructural Atlas of the Inner Ear*. London, Butterworth & Co., 1984.

Janfaza P, Nadol JB. Temporal Bone and Ear. In: Janfaza P ed. *Surgical Anatomy of the Head and Neck*. Philadelphia, Lippincott Williams & Wilkins, 2001:419-479.

Wall C, Vrabec JT. Vestibular Function and Anatomy. In: *Head & Neck Surgery-Otolaryngolog.* Philadelphia, Lippincott Williams & Wilkins, 2001:1641-1650.