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PhysicalTherapy.com

February 9, 2018

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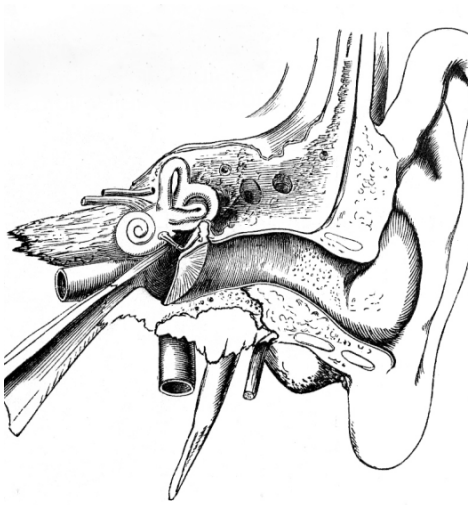
Vestibular System Anatomy and Physiology: An Update



Learner Outcomes

- Identify the main components of anatomy of the vestibular system and explain the functions of each of these components
- Understand the basic physiology of the vestibular hair cells and the push/pull mechanism of the vestibular system and compare/contrast the vestibular hair cell mechanism to a more standard sensory cell
- Identify the main ascending and descending targets for afferent vestibular data and describe the function (as related to balance and/or dizziness) of each target
- Identify the efferent tracts that arise from the vestibular system and explain the impact of efferent vestibular data on function
- Describe the function of the VOR and its relationship to both the visual and vestibular systems

5

Vestibular Problems that impact Function

- Dizziness
- Vertigo (sense of spinning)
- Imbalance
- Visual fatigue or blurring
- Headache

6

Incidence & Prevalence of Dizziness

- 8 million primary care visits annually
- #1 reason for someone over 65 to consult MD
- Second only to HA in prevalence
- 42% of US population (90 million) will c/o at least once in their lifetime
- Estimated that 85% of dizziness is peripheral

7

Purpose of the Vestibular System

- Detects head angular velocity and linear acceleration
- Orients the head and body to gravity
- Newest research: Contributes to spatial navigation, memory and bodily self consciousness (Pfeiffer et al, 2014)

8

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Functions of the Vestibular System

- Stabilize gaze: Stabilizes visual images on the fovea during head movements ➔ VOR (Vestibular Ocular Reflex)
- Control Posture: Keep the body balanced, especially while the head is moving
- Provide information used for spatial orientation
- Coordinate head and body movements
- Encode head position and movement in 3D space

9

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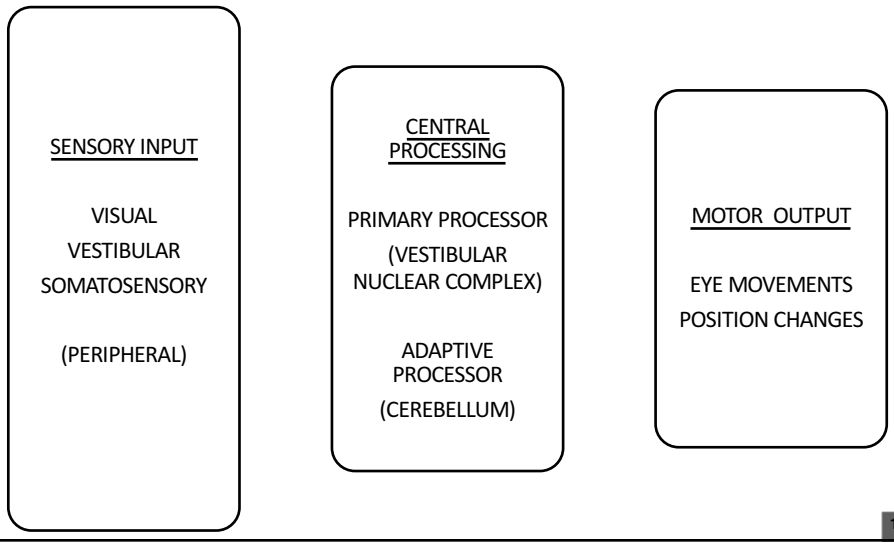
Works in Conjunction with Visual and Somatosensory Data



10

Human Vestibular System

- Peripheral Sensory Apparatus
  - 3 Semi CC and 2 Otoliths
- Central Vestibular System
  - Mechanism for Motor Output and Sensory Integration: Ascending and Descending Tracts

11

Central Vestibular System

- Vestibular nuclei
- Vestibular Cerebellum
- Vestibulococular pathway
- Vestibulospinal pathways
- Vestibular areas in the cortex

12

ANATOMY

- External
- "Inner" ear
- Vestibular Nerve
- Central Processing

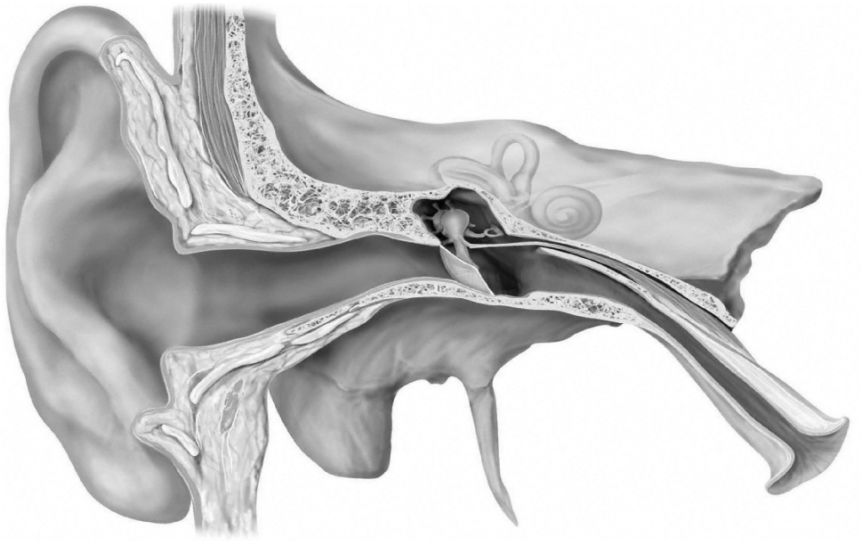
13

External Anatomy

- External Canal
- Tympanic membrane
- Middle Ear
- Oval Window
- Inner Ear

- **All of the above structures except the external canal are enclosed within the temporal bone**

14



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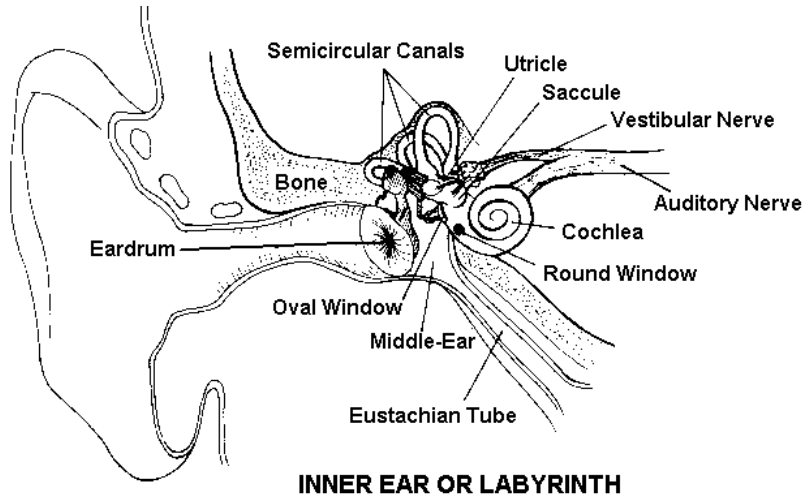


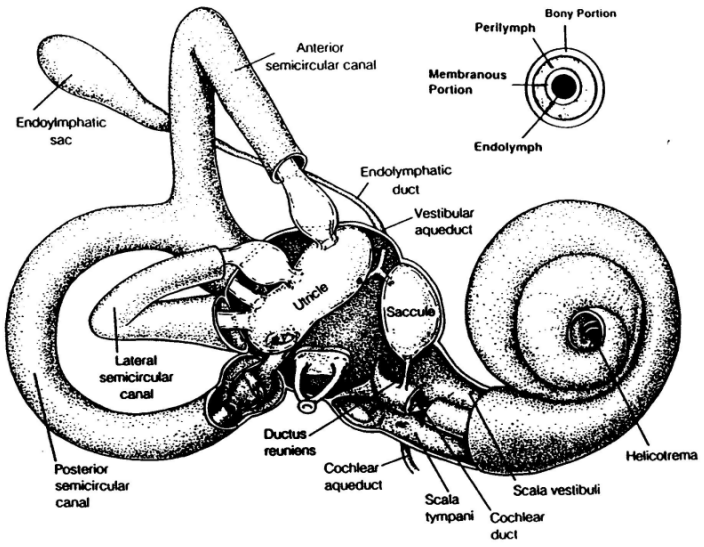
INNER EAR OR LABYRINTH

16

Inner Ear Anatomy

- Vestibule (Central Chamber)
- (3) Semi Circular Canals (per side)
  - Anterior
  - Posterior
  - Lateral
- (2) Otoliths (per side)
  - Utricle
  - Saccule
- Cochlea

17



18

Central Chamber

- Central Chamber (Vestibule) ➔ Filled with perilymphatic fluid (High Na:K ratio, similar to CSF)
- Perilymphatic fluid communicates via cochlear aqueduct with CSF in the subarachnoid space

19

3 SEMI-CIRCULAR CANALS Per side

- Anterior (Superior): Nodding of the head
- Posterior (Inferior): SB
- Horizontal (Lateral): Rotation
- Ampula: Articulates with Utricle

20

Semi Circular Canals

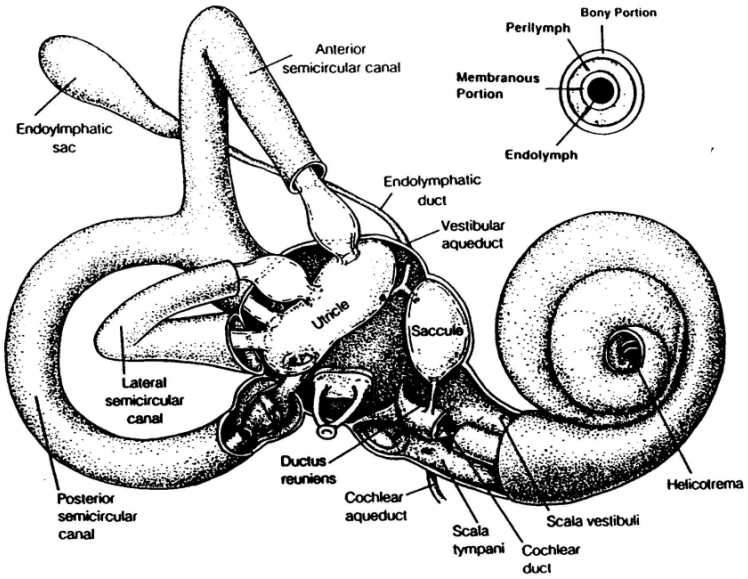
- Bony Labyrinth
- Membranous Labyrinth located INSIDE the bony labyrinth
- Ampula: Widening at the base of each semi circular canal

21

Membranous Labyrinth

- Suspended within bony labyrinth by fluid and supportive connective tissue
- Surrounded by perilymph
- Filled with endolymphatic fluid (High K: Na ratio, like intracellular fluid)
- No direct communication between endolymph and perilymph
- Endolymph is absorbed in endolymphatic sac
- Contains the sensory organs: Crista ampullaris & cupula (Inside the Semi Circular canals)

22

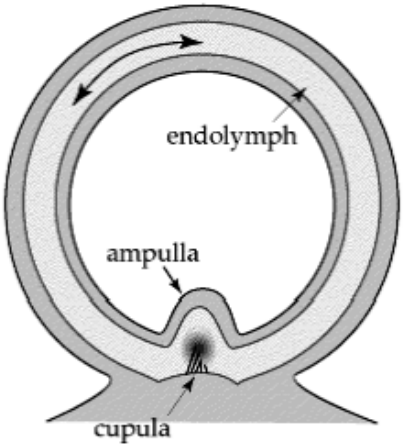


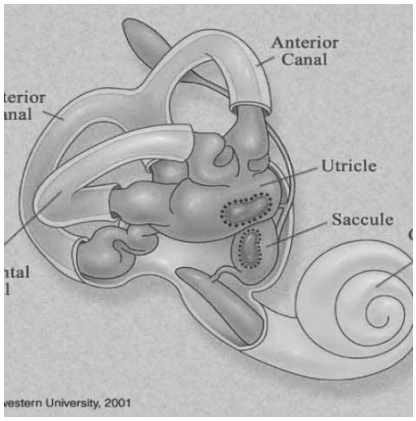
23

Sensory Organ of Semi-CC

- Located within the membranous labyrinth inside a structure known as the *ampula*
- Crista Ampullaris: Base of the cupula
- *Cupula: Gelatinous mass*

24





25

Semi-Circular Canals

- 3 Canals on each side
- Detect Angular VELOCITY
- Horizontals work as a pair
- Anterior canal works with posterior canal of opposite side
- Planes of canals are not directly in line with treatment plane but closer to planes of extraocular muscles
- Provide sensory input re: angular head velocity ➔ Vestibular Ocular Reflex (VOR) generates eye movement that matches head velocity

26

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Alignment of Canals

- Canals are aligned to the planes of the oculomotor muscles (not standard treatment planes)
- Horizontal (Lateral) canal inclined 30 degrees from horizontal plane
- Superior/posterior canals 45 degrees from sagittal plane
- All angular head movements stimulate at least 2 canals, often all 3

27

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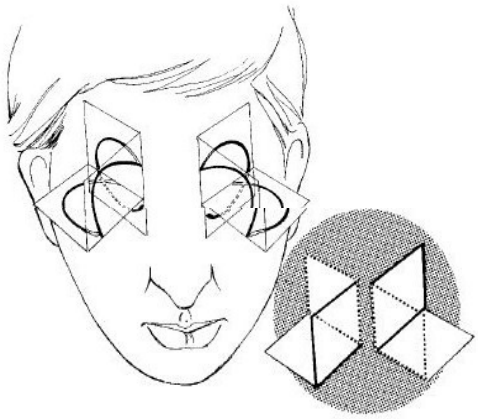

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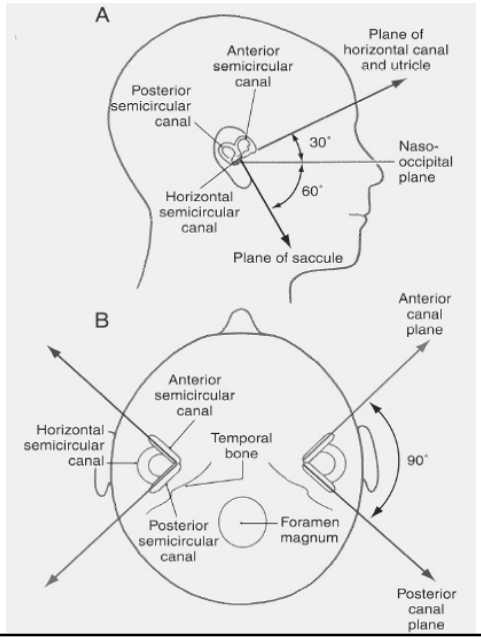
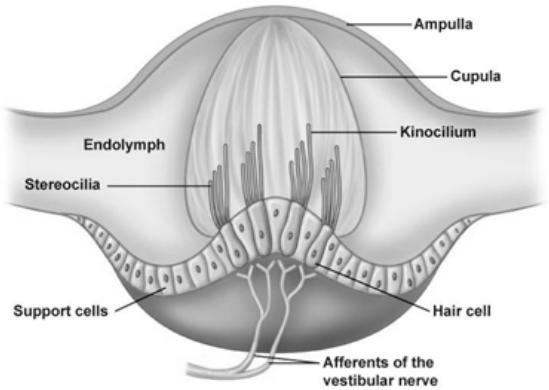

A
Plane of horizontal canal and utricle
Anterior semicircular canal
Posterior semicircular canal
30°
Naso-occipital plane
60°
Horizontal semicircular canal
Plane of saccule
B
Anterior canal plane
Anterior semicircular canal
Horizontal semicircular canal
Temporal bone
90°
Posterior semicircular canal
Foramen magnum
Posterior canal plane

29

Cupula


Ampulla
Cupula
Kinocilium
Endolymph
Stereocilia
Support cells
Hair cell
Afferents of the vestibular nerve

30

Cupula

- *Cupula: Gelatinous mass*
- Located inside the *ampula*
- Hair Cells: *Primary receptor;* extend from the primary afferent nerve of vestib system, through crista ampullaris into cupula

31

PHYSIOLOGY

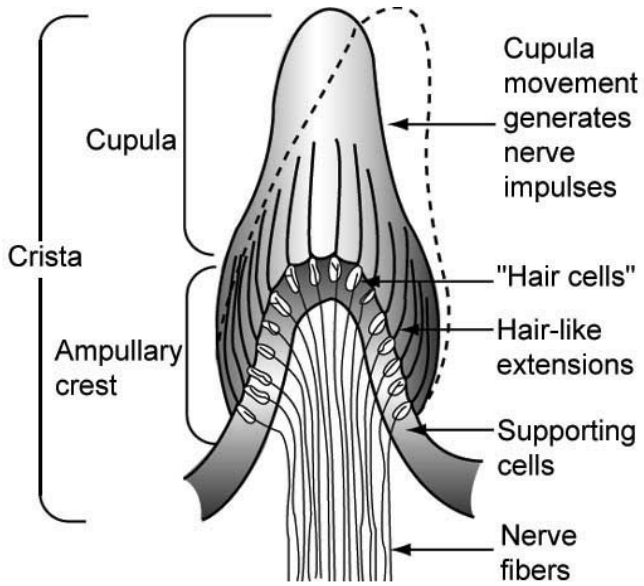
- Movement of fluid (endolymph)
- Deflection of hair cells (within the cupula)
- Each hair cell has a corresponding afferent neuron
- Action potential on what eventually becomes CN VIII

32

PHYSIOLOGY: Ampulla

- Two types of hair cell receptors
  - Type I: Phasic receptors
  - Type II: Tonic receptors
- Movement of head ➔ Movement of endolymph ➔ movement of crista ampularis ➔ deflection of hair cells
- Each hair cell has a corresponding afferent neuron. These neurons have a baseline firing rate
- When hair cells are deflected towards the utricle (toward kinocilium) ➔ Excitation
- When hair cells are deflected away from the utricle ➔ Inhibition

33



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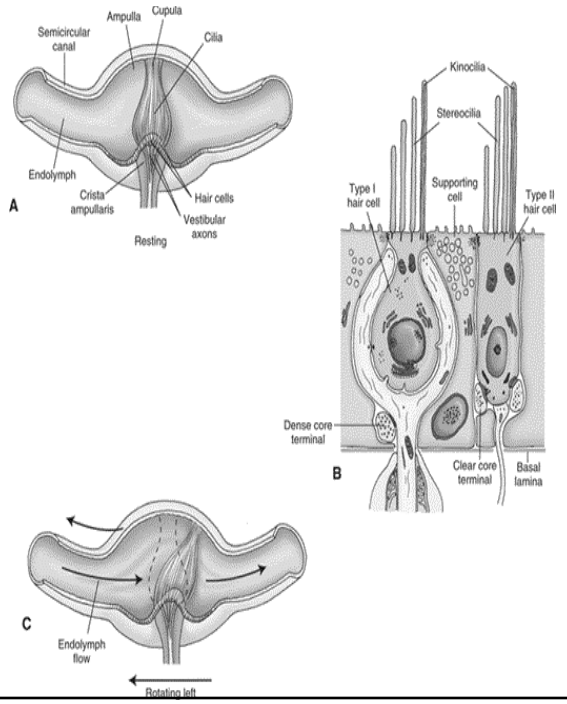

35

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Questions?

36

Otoliths

- Utricle: Larger; Located in the transverse plane; all 3 canals originate and terminate on it; when head horizontal, sensory organ of utricle is nearly horizontal
- Saccule: Smaller, located in the sagittal plane, more distal from canals; when head is horizontal, saccule is nearly vertical
- Sensitive to *gravity* and *linear acceleration*

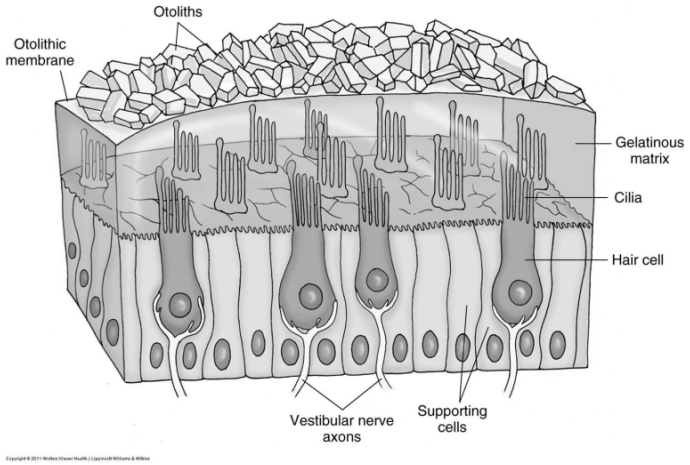
37

Sensory Organs within otoliths

- Macula of the Saccule
- Thickened area of ectoderm
- Contain supporting cells and hair cell receptors
- Otolithic membrane (gelatinous plate)
- Carbonate crystals

38

Macula



39

PHYSIOLOGY

- Movement of fluid
- Deflection of hair cells
- Action potential on what eventually becomes CN VIII

40

PHYSIOLOGY

- Detection of movement: Gravity, head & neck movement
- Receptors: Otoliths and SCC
- Hair Cells are located within BOTH types of receptors
- Deflection of hairs cells due to head movement stimulates the action potential
- Different types of movements deflect hair cells, but, otoliths and SCC function is based on movement of hair cells

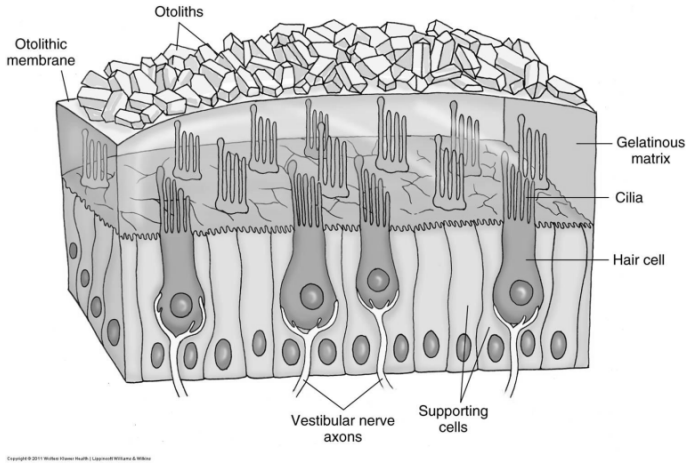
41

Physiology: Macula

- Cilia of hair cells embedded in otolithic membrane
- Each hair cell has a carbonate crystal on its end: otoconia
- With no head movement: Hair cells only respond to the pull of gravity ➔ static response code
- Linear acceleration or deceleration of the head also displaces otolithic membrane

42

Macula



43

Vestibular Nerve

- Cranial Nerve VIII
- Carries sensory data both from the vestibular system and from the cochlea
- Also known as the:
  - "Vestibulo-cochlear Nerve"

44

Vestibular Nerve

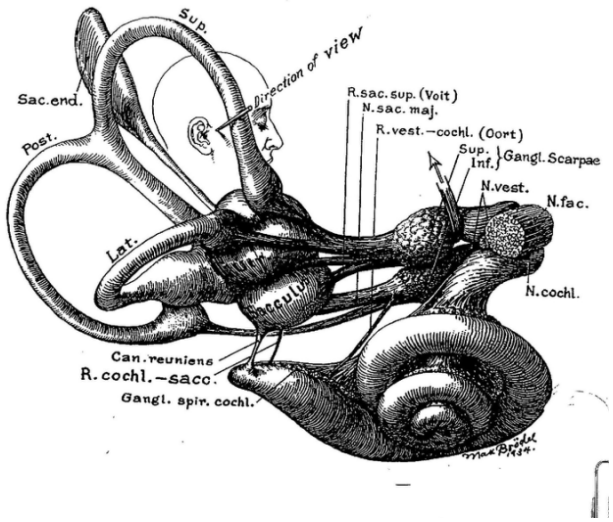
- Contains two divisions: Superior and Inferior
- Superior ➔ Utricle, horizontal and and anterior SCC
- Inferior ➔ Saccule and Posterior SCC
- Individual branches enter Scarpa's Ganglion first, then emerge and form CN VIII

45

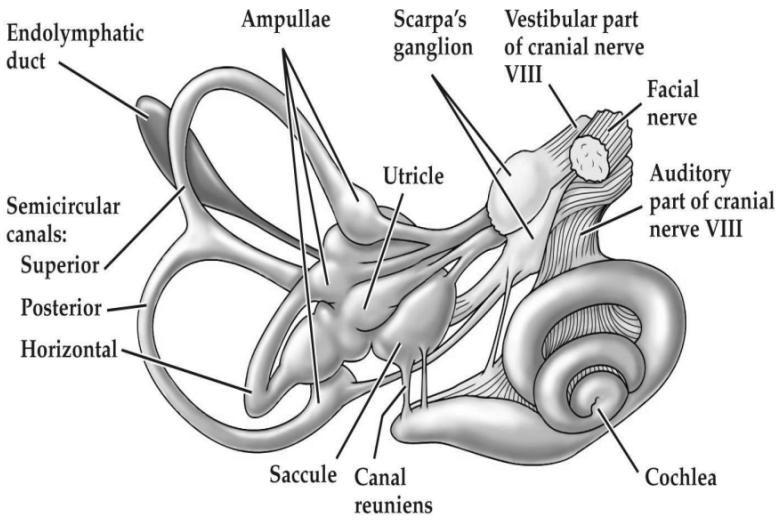
Vestibular Nerve

- Primary afferents reside in Scarpa's ganglion (also known as vestibular ganglion)
- Contains bipolar ganglion cells of first order neurons
- Scarpa's ganglion is in the internal auditory canal

46


Sup.
Direction of view
Sac.end.
Post.
Lat.
R.sac.sup. (Voit)
N.sac. maj.
R.vest.–cochl. (Oort)
Sup.
Inf.
Gangl. Scarpae
N.vest.
N.fac.
N.cochl.
Can.reuniens
R.cochl.–sacc.
Gangl. spir. cochl.

47


Endolymphatic duct
Ampullae
Scarpa's ganglion
Vestibular part of cranial nerve VIII
Facial nerve
Utricle
Auditory part of cranial nerve VIII
Semicircular canals:
Superior
Posterior
Horizontal
Saccule
Canal reuniens
Cochlea

48

Vestibular Nerve

- Each hair cell sends an individual afferent projection to Scarpa's gaglion
- Use either aspartate or glutamate (excitatory)
- Central processes from both ganglion unite to form the vestibular division of CN VIII
- No primary vestibular afferents cross the midline
- SSA: Special Somatic Afferent

49

Central Processing of Vestibular Input

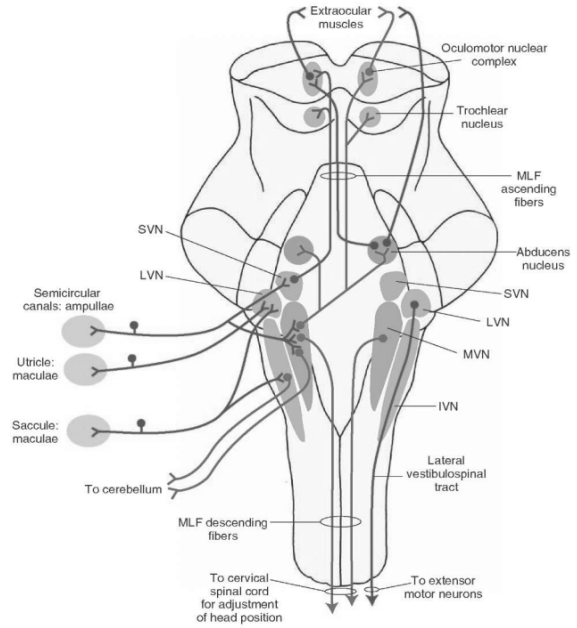
- Main Targets:
  - Vestibular Nuclear Complex
  - Cerebellum
- Other Targets:
  - Motor nuclei of the extra-ocular muscles

50

Vestibular Nuclear Complex

- Located in the rostral medulla caudal pons
- Immediately adjacent to 4th ventricle
- 4 Major Nuclei: Superior, medial, lateral (Deiter's) & Inferior (descending spinal)

51



52

Vestibular Nuclear Complex: Overview

- Superior & Medial ➔ Relays for VOR
- Medial ➔ Vestibulospinal reflexes; coordinates head/eye movements that occur together
- Lateral ➔ Principle nucleus for vestibulospinal reflex
- Inferior ➔ Connected to all others and CB; no primary output of it's own

53

Vestibular Nuclei	Peripheral Structure	Location/Function
Medial	Semi CC	Descending to muscles of the head/neck via MLF ➔ Head position/control
Superior Vestib N	Semi CC	Ascending output via MLF to oculomotor Nuclei (CN 3, 4 , 5) for VOR
Lateral (Deiter's)	Utricle and Saccule	Output to CB for feedback; Contributes of LVST to engage the postural muscles of the Trunk/LE's
Inferior (Descending spinal)	Utricle	Output to CB for feedback; Output to Reticular formation for arousal and autonomic function; output to CN 3, 4, 6 for VOR

54

Vestibular Nuclei: Efferent output that Ascends

- SVN ➔ Ascending MLF ➔ Abducens (CN VI); Trochlear (CN IV) & Oculomotor Nuclei (CN III)
  - CN VI: Lateral rectus
  - CN IV: Superior Oblique
  - CN III: Inferior Oblique; medial, superior & inferior rectus
- MVN ➔ Ascending MLF➔ Extraocular nuclei (CN III, IV and VI) & Interstitial nucleus of Cajal
- IVN ➔ Ascending MLF ➔ Trochlear N & Oculomotor Nuclei; Also to CB

55

Vestibular Nuclei: Efferent Output that Descends

- LVN ➔ LVT ➔ Lamina IX ➔ alpha MN (cholinergic ➔ Excitatory)
- MVN ➔ MLF ➔ Lamina VII & VIII in C-spine segments. Inhibitory or excitatory. Also known as the medial vestibulospinal tract
- IVN ➔ Inferior olivary nucleus ➔ medial reticular formation ➔ CB & C-spine segments

56

Vestibular Nuclei: Summary

- Principally motor reflex connections to nuclei innervating extraocular muscles, motor reticular formation, spinal motor neurons and CB
- Other projections to Cerebral cortex, via the dorsal thalamus

57

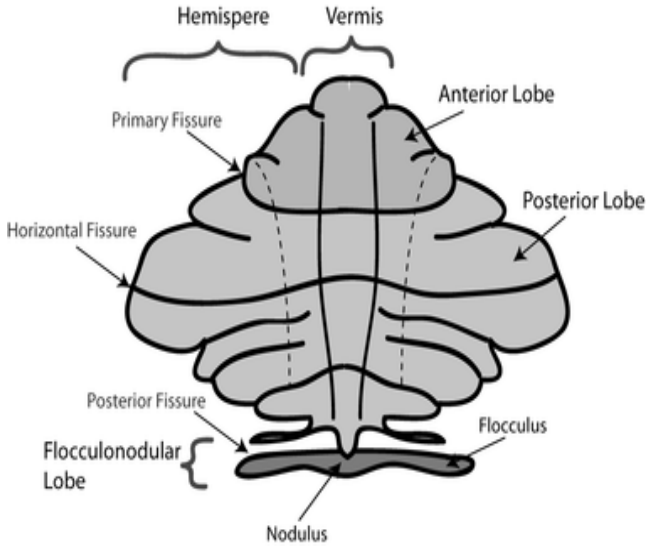
QUESTIONS???

58

Cerebellum

- Major recipient of outflow from vestib nuclear complex
- Major source of input to the vestib nuclear complex via direct projections to vestib nuclei
- Vestibular labyrinth: Only sensory organ to send primary afferent fibers directly to CB
- Vestib system also sends second order afferent fibers to CB (SVN, MVN & IVN)
- The CB is largely inhibitory to Vestib N

59



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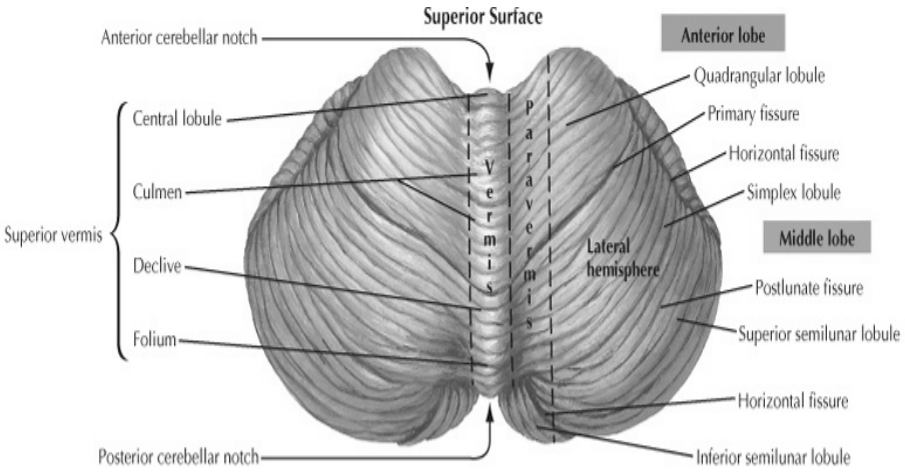
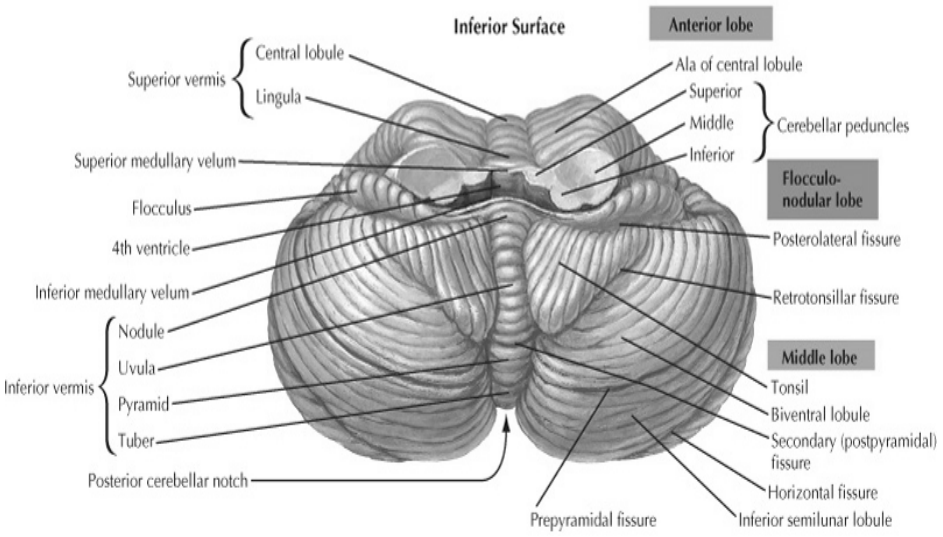


61

Cerebellum

- Most portions of the Vermis (Cerebellar midline) respond to vestibular stimulation
- Flocculus, nodulus, uvula and fastigial nucleus are sometimes referred to as the "Vestibular Cerebellum"

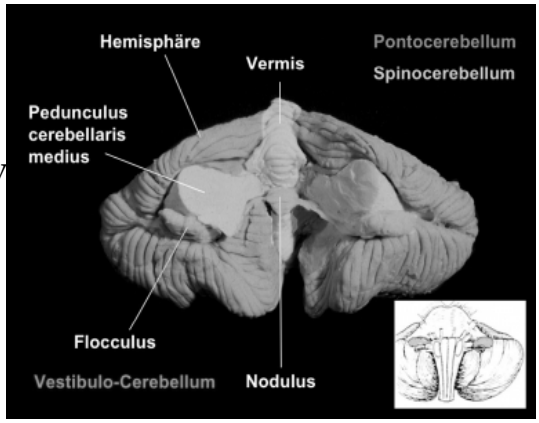
62



63

Flocculus

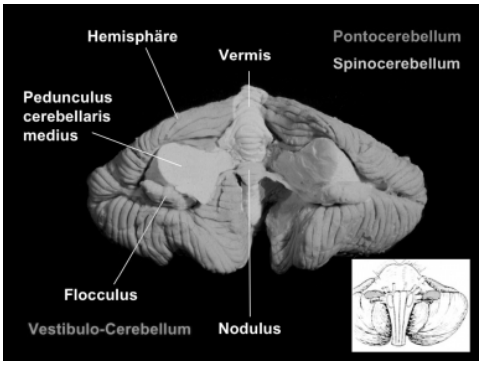
- Adjusts and maintains the gain of the Vesibulo Ocular Reflex (VOR)
- Lesion here ➔ Difficulty adapting the VOR



64

Nodulus

- Adjusts duration of the VOR
- Processes otolith info
- Lesion: Nystagmus that changes with head position



65

Ocular Cerebellar Signs

- Downbeat or direction changing gaze evoked nystagmus
- Saccadic intrusions with VORc AND/OR smooth pursuit
- Spontaneous nystagmus – Failure to suppress with fixation
- Hypermetric Saccades

66

Vestibular Reflexes

Vestibulo-Spinal
Vestibulocollic
Vestibular Ocular

67

Vestibular Reflexes

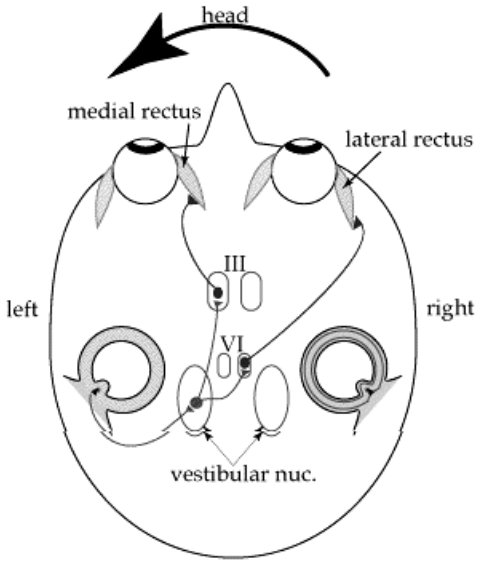
- Vestibular Ocular
  - Stabilizes the visual image during head movement
- Vestibulo-Spinal
  - Senses falling; Contracts the limb muscles for postural support
- Vestbulocollic
  - Acts on the neck muscles to stabilize the head on the body; stabilizes the head when the body moves

68

VOR: Vestibular Ocular Reflex

- Keeps the eyes steady while the head is moving
- Angular VOR: Mediated by Semi CC ➔ Gaze stabilization
- Linear VOR: Mediated by Otoliths ➔ compensates for translation

69



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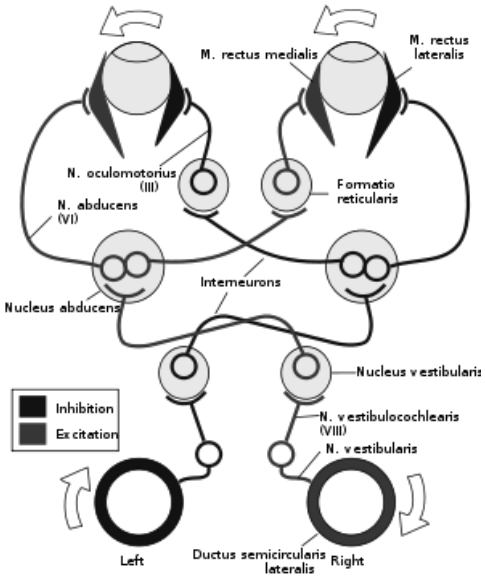


71

Vestibulospinal Reflex

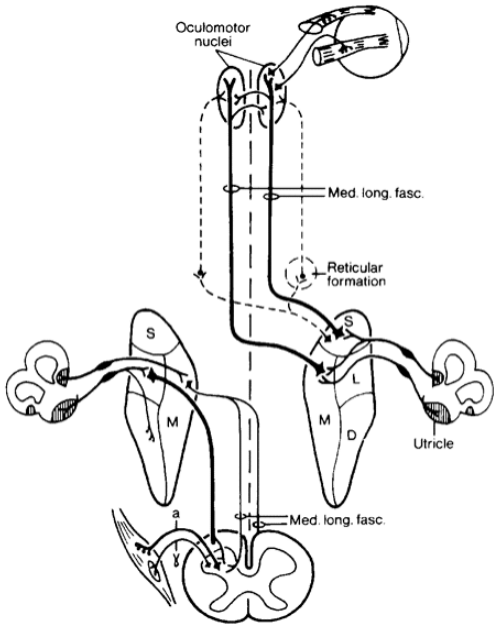
- Senses head movement and head relative to gravity
- Contracts limbs muscles for postural support
- Output to anterior horn cells that innervate Extensors of neck, trunk and extremities
- Must use Otolith input
- Projects to antigravity muscles via 3 major pathways:
  - Lateral vestibulospinal tract
  - Medial vestibulospinal tract
  - Reticulospinal tract

72

Vestibulospinal Reflex

- Helps maintain upright posture in reference to gravity
- Keeps the body stable during head motion
- Maintains equilibrium of the body during movement
- Maintains background muscle tone (in conjunction with the Cerebellum)
- More complex pattern of activation than the VOR, most likely a compilation of several reflexes as opposed to just one reflex
- Fewer studies on the VSR (compared to VOR) due to its complexity

73



74

Vestibular Cortex

- There does not appear to be a unisensory vestibular cortex in the human brain (ie: One place in the CNS where all the vestibular data converge, occipital cortex)
- Rather, vestibular data is distributed throughout the cortex
- These areas often overlap with areas receiving other sensory data (vision, proprioception)

75

Vestib Connections to the CNS

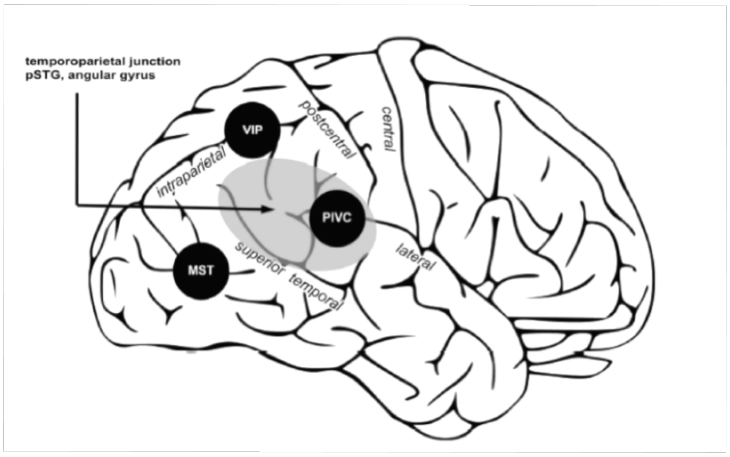
- Lopez & Blanke (2011): Stimulation of the Semi CC either via calorics or galvanic stimulation reveals activation in multiple areas of the:
  - Parietal Cortex
  - Temporal cortex
  - Insular Cortex
  - Frontal Cortex
  - Occipital Cortex
  - Thalamus

76

Vestib Connections to the CNS

- Pfeiffer et al (2014) suggest the Parietoinsular Vestibular cortex (PIVC) encodes vestibular stimulation and proprioceptive signals from cervical musculature. Other authors (zu Eulenberg et al, 2012) suggest the PIVC is the vestibular input areas in the human cortex. HOWEVER ➔ NO consensus re: the human Vestibular Cortex. Many suppositions

77



Vestib Connections to the CNS

78

SUMMARY

79

QUESTIONS?

80

CONTINUED

REFERENCES

- Herdman (2007). Vestibular Rehabilitation, 3rd Edition. FA Davies
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81

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82