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Anatomy & Physiology of the Vestibular System
Learning Objectives

• After this course learners will be able to:
• Identify the main components of anatomy of the vestibular system.
• Describe the basic physiology of the vestibular hair cells and the push/pull mechanism of the vestibular system.
• 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.
• Describe the function of the VOR and its relationship to both the visual and vestibular systems.

Vestibular Problems that impact Function

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

Purpose of the Vestibular System

- Detects head angular velocity and linear acceleration
- Orients the head and body to gravity
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

Works in Conjunction with Visual and Somatosensory Data

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<table>
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<th>MOTOR OUTPUT</th>
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<td>EYE MOVEMENTS POSITION CHANGES</td>
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3 components to the Human Vestibular System

• Peripheral Sensory Apparatus
• Central Processor
• Mechanism for Motor Output and Sensory Integration: Ascending and Descending Tracts

ANATOMY

• External
• “Inner” ear
• Vestibular Nerve
• Central Processing
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
Inner Ear Anatomy

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

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

Semi Circular Canals: Anatomy

- Bony Labyrinth
- Membranous Labyrinth located INSIDE the bony labyrinth
- Ampula: Widening at the base of each semi circular canal
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)
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*
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
Canals are not aligned directly in the treatment planes

- Canals are aligned to the planes of the oculomotor muscles
- 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
Functions of the Cupula

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
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

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
Sensory Receptors of the Vestibular system

Questions?
Otoliths (2 per side)

- 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 saggital plane, more distal from canals; when head is horizontal, saccule is nearly vertical
- Sensitive to gravity and linear acceleration
Macula of the Saccule &
Macula of the utricle

Located within:
Saccule and Utricle

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
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
PHYSIOLOGY: 101

- Movement of fluid
- Deflection of hair cells
- Action potential on what eventually becomes CN VIII
PHYSIOLOGY: Who can stop at 101?

- 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

Physiology: Macula

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Macula

Otoconia: calcium carbonate crystals

Otolithic membrane

Hair cells

Macula

Vestibular nerve

Otoliths

Gelatinous matrix

Cilia

Hair cell

Vestibular nerve axons

Supporting cells
Vestibular Nerve

- Cranial Nerve VIII (Vestibulo-cochlear Nerve)
- Carries sensory data both from the vestibular system and from the cochlea
- Travels in the Internal auditory canal along with the facial nerve and labyrinthine artery
- Enters the brainstem at the ponto-medullary junction

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
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
Vestibular Nerve

- Each hair cell sends an individual afferent projection to Scarpa’s ganglion
- 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
Central Processing of Vestibular Input

- **Main Targets:**
  - Vestibular Nuclear Complex
  - Cerebellum
- **Other Targets:**
  - Cell groups: f, x, y, z (minor vestibular nuclei)
  - Motor nuclei of the extra-ocular muscles

Vestibular Nuclear Complex

- From Scarpa’s Ganglion
- Along CN 8
- 4 Vestibular Nuclei
  - Superior
  - Medial
  - Lateral
  - Inferior (Deiter’s)
- Minor Nuclei: f, x, y and z
- Located in the rostral medulla & caudal pons
Vestibular Nuclear Complex: General Function

- 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
Vestibular Nuclear Complex: Afferent input

- SVN $\rightarrow$ Input from SCC
- MVN $\rightarrow$ Input from SCC
- LVN $\rightarrow$ Input from other nuclei and utricle/saccule
- Inferior $\rightarrow$ Input from Saccule

Vestibular Nuclei: Efferent output that Ascends

- SVN $\rightarrow$ MLF $\rightarrow$ Abduces (CN VI); Troclear (CN IV) & Oculomotor Nuclei (CN III)
  - CN VI: Lateral rectus
  - CN IV: Superior Oblique
  - CN III: Inferior Oblique; medial, superior & inferior rectus
- MVN $\rightarrow$ MLF $\rightarrow$ Extraocular nuclei (CN III, IV and VI) & Interstitial nucleus of Cajal
- IVN $\rightarrow$ MLF $\rightarrow$ Troclear & Oculomotor Nuclei
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 nuclues → medial reticular formation → CB & C-spine segments

Pathways
Vestibular Nuclei

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

QUESTIONS???
Cerebellum

• Major recipient of outflow from vestib nuclear complex
• Major source of input to the vestib nuclear complex via direct projections to vestib nuclei
• Parts of the CB adjust the GAIN of the VOR and duration of VOR response
• 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)

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”
CONTINUED
Vestibular Reflexes: VOR and VSR

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
Vestibulospinal Reflex

- Senses head movement and head relative to gravity
- 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
Vestibulospinal Reflex

- Helps maintain upright posture in reference to gravity
- 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
QUESTIONS?

Helpful Web Resources

- Vestibular SIG of the Neurology section
- You Tube
- Geriatric Examination Tool Kit
- VEDA (www.vestibular.org)
REFERENCES