Anatomy and Physiology of the Vestibular System

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Overview

- Angular movements stimulate semicircular canals and are primarily important for visual stabilization
- Semicircular canals paired with a contralateral semicircular canal (i.e., R Lat SCC with L Lat SCC)
- Movement in any plane stimulates one SCC and inhibits corresponding SCC on the opposite side
- Otolithic labyrinth (utricle and saccule) respond to linear movement and primarily orient with regard to gravity
- Static tilt results in continued stimulation
**Vestibular Hair Cells**

- Stereocilia
- Kinocilium
- Resting firing rate of 90 spikes/sec
- Increased firing rate when deflection towards kinocilium

**Anatomy**

**Semicircular Canals**

- Orientation
- Ampulla

**Physiology**

**Semicircular Canals**

- Push pull interaction
- VOR

**Central Vestibular System**

- Sup SCC, Lat SCC, utricle and ant/sup portion of saccule innervated by Superior Vestibular Nerve
- Post SCC and majority of saccule innervated by Inferior Vestibular Nerve
- VIII consists of bipolar neurons with cell bodies in Scarpa’s Ganglion in IAC
- Vestibular Nuclei in brainstem
Vestibulo-Ocular Reflex

- Stabilizes gaze during active head movements
- Absent VOR results in bouncing environment while walking, riding in car or other activities (oscillopsia)
- Superior Vestibular Nerve synapses in medial and superior vestibular nuclei then on to MLF and III, IV, and VI
- Second VOR pathway is multisynaptic

Physiology
Otolithic Organs

- Otoconia
- Resting neural discharge
- Linear acceleration

Anatomy
Otolithic Organs

- Orientation
- Macula

Central Vestibular System

- Otolithic neural signals synapse in medial and lateral vestibular nuclei
- Second order neural signals extend to anterior horn cells of cervical cord (medial vestibulospinal tract) and entire spinal cord (lateral vestibulospinal tract)
- Innervate antigravity muscles of neck, thorax and lower limbs
- Also supplies EOM’s to produce rotational and vertical ocular adjustments during head tilt
- Cerebellum produces inhibitory influence through Purkinje cell activity which fine tunes response and assures proper interaction with visual and proprioceptive cues
- Ascending vestibulocortical pathways provide conscious awareness of body orientation
Ocular Motor Control

Saccadic Eye Movements

• Reflexive eye movements that occur during vestibular or optokinetic stimulation
• Returns eye to neutral position
• Characteristics
  – Conjugate deviation
  – High velocity (200 – 600 degrees/sec)
  – Accuracy
  – Short Latency (<250 msec)

Smooth Pursuit Eye Movements

• Generates smooth conjugate eye movements to track small, discrete, slowly moving objects
• Visual information (via visual cortex) compared to vestibular information in vestibular nuclei then on to oculomotor nuclei
• Declines with age, changes in visual acuity, target speed, sedation, inattention and CNS pathology

Optokinetic Eye Movements

• Driven by full field peripheral retinal stimulation
• Same neural pathway as smooth pursuit
• Deficits parallel smooth pursuit dysfunction

Visual Vestibular Interaction

• VOR keeps object stable with head is moving
• Visual tracking systems (saccadic, pursuit and OPK) follow object in motion when head is stable
• When head is moving and object is moving both systems must work together
• With vestibular injury, smooth pursuit and OPK make up partially for loss of vestibular cues and VOR
Unilateral Vestibular Loss

- Damage to one labyrinth results in asymmetric input from the vestibular system
- Results in slow deviation toward damaged ear and saccadic reset towards intact ear
- Results in sensation of self movement (vertigo) towards intact ear
- CNS suppression of nystagmus (cerebellar clamp effect) within hours to days occurs
- Over weeks, rebalancing of dynamic asymmetry occurs to create a more meaningful eye movement during head rotation

Bilateral Vestibular Loss

- May occur from ototoxicity, trauma or autoimmune disorders
- Peripheral loss may not be asymmetric with lack of vertigo and spontaneous nystagmus
- Oscillopsia results from absent VOR and retinal slippage of image
- Oculomotor systems (smooth pursuit and OPK) can partially substitute for VOR at slower head movements (<100 degrees/sec)
- With training, saccadic systems can replace deficient VOR at higher velocities (100 – 200 degrees/sec)
- Nothing can replace VOR at high velocities (>200 degrees/sec) resulting in oscillopsia

Somatosensory Input

- Pressure receptors on soles of feet combined with stretch receptors from cervical, thoracic and lumbar musculature
- Both monosynaptic (knee jerk) and multisynaptic (long motor arc reflex)
- Impaired in peripheral neuropathy
  - Sensory
  - Motor
- With vestibular loss, lack of somatosensory input causes more significant problems
Dynamic Equilibrium

- Determination of Body Position
- Choice of Body Movement
- Compare, Select and Combine Senses
- Select and Adjust Muscle Contractile Pattern
- Generation of Body Movement

Maintenance of Posture

- Visual and somatosensory input compared with vestibular cues to keep COG over feet
- Eccentric COG results in corrective motor response
  - Ankle response
  - Hip response
  - Step response

Summary

1. SCC sense angular acceleration to aid in gaze stabilization during head movement (VOR)
2. Otolith organs (utricle and saccule) sense linear acceleration and gravity changes to promote compensatory postural and oculomotor responses
3. Cerebellum controls both systems to assure appropriate motor activity and sensory integration
4. Vestibular nuclei are critical for sensory integration
5. Thalamus and cerebral cortex play an important role in motion perception
6. Normal balance and oculomotor control occur at a subconscious level

Vestibular Function Testing

William J. Eblin, Jr., Au.D.
Assessment of the dizzy patient

- History
- Exam
- Testing

Goals of Testing

- Completely assess vestibular system
- Site and extent of lesion
- Functional performance/objectify complaints
- Determine status of compensation
  - Physiologic Compensation
  - Functional Compensation
- Help determine who may be appropriate for rehab

Anatomy Overview

- **Semicircular Canals**
  - Sensitive to rotation
- **Otoliths**
  - Sensitive to linear accelerations
    - Utricle
    - Saccule

Key Concepts

- **Nystagmus**
  - Slow phase ("drift") → vestibular system
  - Fast Phase ("beat") → brainstem

- Acute labyrinthine loss...
  - Eyes drift toward the side of lesion, "beat" toward better ear
  - Example: left ear hypofunction
    - Because left ear "pulls" eyes to the right, eyes drift left
    - Snap back (beat) to the right (mediated by the brainstem)
### Key Concepts: Spontaneous Nystagmus

- Nystagmus always beats toward the more active neural side
  - Acute right vestibular hypofunction: left beating spontaneous nystagmus
- Alexander’s Law: nystagmus intensifies when looking toward quick phase of nystagmus
- Exception: irritative lesions
  - e.g., Meniere’s Disease
    - Diseased labyrinth has increased neural activity

### Key Concepts: Peripheral vs. Central Spontaneous Nystagmus

- **Fixation**
  - Peripheral: decreases
  - Central: no change or increases
- **Direction**
  - Peripheral: most often mixed direction; torsional and horizontal
  - Central: usually single plane; vertical or horizontal
- **Gaze effects**
  - Peripheral: increases with gaze toward quick phase
  - Central: no change or reverses direction

### Central Nystagmus Signs

- Downbeat nystagmus
- Upbeat nystagmus
- Periodic alternating nystagmus

### Contemporary Vestibular Assessment

- Audiometrics
- Computerized Dynamic Posturography
- Rotational Testing
- VNG/ENG
- VEMP
  - Cervical
  - Ocular
- Subjective Visual Vertical
Additional Tests

- Postural Tests
  - Modified Clinical Test of Sensory Interaction on Balance (mCTSIB)
  - Limits of Stability (LOS)
- Dynamic Visual Acuity (DVA)
- Gaze Stabilization Test (GST)
- Unilateral Centrifugation
  - w/ SVV

So...what are we assessing?

- Horizontal SCC / Superior Vestibular Nerve
  - Caloric Testing
  - Rotational Testing
  - Dynamic Visual Acuity
- Saccule / Inferior Vestibular Nerve / Central Pathways
  - cVEMP
- Utricle / Central Pathways
  - oVEMP
  - SVV

Tests that are less specific...

- Do not specifically measure labyrinth or vestibular nerve:
  - Oculomotor testing
  - Computerized Dynamic Posturography

What are we assessing?

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Audiometric Evaluation

- Provides information about the auditory system
- Helpful in the identification of retrocochlear pathology
- Health of EAC and middle ear before testing
  - i.e., intact TM prior to caloric testing
  - Conductive/Mixed HL prior to VEMP testing
- Useful to identify patterns associated with vestibular and balance disorders
  - Vestibular labyrinthitis
  - Meniere’s
  - Acoustic neuroma
  - Etc.

Audiometric Evaluation

- Audiogram
- Tymps / Reflexes (ipsi and contra)
- OAE’s
  - Cochlear vs. neural pathology

Contemporary Vestibular Assessment

- Audiometrics
- **Computerized Dynamic Posturography**
- Rotational Testing
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Computerized Dynamic Posturography

- Balance requires integration of information sent by the peripheral systems received at the cerebellum
- Peripheral sensors:
  - Visual system
  - Somatosensory system
  - Vestibular system

Computerized Dynamic Posturography

- Identifies impairment – functional component
  - Impairment, not pathology
- Identifies patient’s strategy for maintaining balance
- Compensation status
- Treatment guidelines
- Post-treatment measures

Additional advantages

- Objective measure
  - Operator has little influence on outcome
- Identification of malingering
  - Possible to cheat, but patterns can be identified
- Very reliable
- Patient education

CDP Conditions

- 6 conditions; 3 trials in each condition
  1. Eyes open, fixed surround/surface
  2. Eyes closed, fixed surround/surface
  3. Eyes open, moving surround, fixed surface
  4. Eyes open, fixed surround, moving surface
  5. Eyes closed, fixed surround, moving surface
  6. Eyes open, moving surround/surface
- Gradually increasing reliance on vestibular information
CDP Conditions

CDP Measurements

- Equilibrium Score
  - Composite score
  - Limit to human center of gravity (COG) shift
    - 12.5 deg front to back
    - 16 deg laterally
- Sensory Analysis
  - Visual, vestibular, somatosensory...
- Strategy Analysis
  - Ankle / Hip dominance
- COG

Test Tip...

- Test each condition before repeating trial in a condition
  - 1, 2, 3, 4, 5, 6 x 3
CDP Video

CDP Patterns

- Vestibular pattern
  - Conditions 5/6
- Visual preference
  - Conditions 3/6
- Surface dependent
  - Conditions 4, 5, and 6
- Visual pattern
  - Conditions 2, 3, 5, and 6
- Functional pattern
  - Better performance on more difficult conditions

Adapted from A. Desmond, "Vestibular Function: Evaluation and Treatment", © 2004
Contemporary Vestibular Assessment

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Rotary Chair Test

- Sinusoidal Harmonic Acceleration (SHA)
- Velocity Step Testing (Step Test)
  - AKA Trapezoidal Testing

Advantages of Rotational Testing

- Precise measurements
- Not reliant on physical features
  - External ear / temporal bone
- Useful in pediatric assessment
- Serial monitoring
- Expansion of test frequency range
  - Calorics: 0.002 – 0.004 Hz
  - Rotational testing: 0.01-1.00 Hz
  - Physiologic range: 0.5 – 7.00 Hz
- Bilateral loss (may show that labyrinth is not “dead”, even if caloric responses are not present)

SHA Testing

- Patient is rotated at specific frequencies from 0.01 – 0.64 Hz
  - Harmonics
    - 0.02 Hz
    - 0.04 Hz
    - 0.08 Hz
    - 0.16 Hz
    - 0.32 Hz
    - 0.64 Hz
- Very good for diagnosing bilateral vestibular loss
- Information about compensation
SHA Testing

• Measure gain, phase, and symmetry for each test frequency

SHA Measurements

• Gain
  – Ratio of the amplitude of peak slow-component eye velocity vs. head velocity
  – Chair movement vs. eye movement

• Phase
  – Timing relationship between eye and head velocity

• Symmetry
  – Eye velocity during rightward vs. leftward movements

SHA Interpretation

• Reduced Gains
  – Labyrinthine loss; implies bilateral hypofunction

• Phase Lead
  – Suggestive of peripheral problem

• Asymmetry
  – Uncompensated vestibular loss
    - Weakness on side of greater slow-component velocity
    - OR
      - Irritative lesion contralateral to side of greater slow-component velocity

• Increased Gains
  – Suggestive of cerebellar lesion

SHA: Compensation

• Compensated unilateral vestibular hypofunction:
  – Phase lead persists
  – Asymmetry no longer present