Vestibular System

Transduction of Head Movements

Why transduce head movements?

• Gaze stabilization
  – Vestibulo-oculomotor
• Orientation & Heading
  – Visual-Vestibular-oculomotor
• Posture & Balance
  – Vestibulo-spinal
  – Vestibulo-neck
Why do we need a vestibulo-oculomotor system?

• To keep the fovea on an object during self-motion (i.e., To prevent slip of images)

What does the vestibular system have to cope with?

• Angular Head movements
  – Canal System
• Linear Head Movements
  – Otolith System
• Gravity/Tilt
  – Otolith System
Angular Head Movements

**PREDOMINANT FREQUENCIES OF HEAD ROTATIONS**

Angular Head Movements

**MAXIMUM VELOCITIES DURING LOCOMOTION**

Leigh and Zee 2006
• A primary source of retinal slip is any kind of *head movement*

• Two strategies for retinal stabilization
  – keep head stationary relative to outside world (chick)
  – use information about head movements to control eye muscles (primates & humans)
  – advantage of second strategy is speed of response

• Source of information of head movements is the vestibular apparatus
  – semicircular canals; information on *angular rotations*
  – otoliths; information on *linear acceleration* *(gravity)*

• VOR is the fast reflex which connects this sensory apparatus to the ocular motoneurons
Vestibulo-ocular reflexes

- Angular Head movements
  - Canal System
    - Angular VOR or Rotational VOR
- Linear Head Movements
  - Otolith System
    - Translational VOR or Linear VOR
- Gravity/Tilt
  - Otolith System
    - Ocular counterrolling

The Angular Vestibulo-ocular Reflex (aVOR)
The aVOR

- Gaze holding mechanism that generates eye movements to compensate for head motion

- Gaze or line of sight is maintained on a stationary target

1) Inner ear anatomy and physiology

2) Properties of the VOR
Bony and Membranous Labyrinth

- Inner ear contains the structures responsible for the VOR
- Inner ear is called the labyrinth because of the complexity of its shape
- Outer part is called the Bony Labyrinth
  - Series of cavities inside the petrous portion of the temporal bone
  - Contains perilymph which is similar to cerebrospinal fluid
  - The temporal bone of the bony labyrinth is one of the hardest bones of the human body
- Inside the bony labyrinth is the membranous labyrinth
  - Takes the same shape as the bony labyrinth
  - Separated from bony labyrinth by perilymph

Membranous Labyrinth
- Cochlea
- Otoliths
  - Utricle
  - Saccule
- Semicircular canals
  - Horizontal
  - Anterior
  - Posterior
Semicircular canals sense angular head acceleration

- Thin tubes that contain fluid called endolymph
- At the base of each canal is an enlarged region called the ampulla
- Inside the ampulla is the crista. Cristae of each canal contain hair cells.

Mechano-electric transduction by Hair Cells
• Processes of hair cells are embedded in the cupula which lies in the ampullae

• Cupula is gelatinous membrane that prevents the free flow of endolymph

How do the SCC sense head motion?

• Acceleration of the head results in movement of fluid in the SCC.
• As the head rotates in one direction, inertia of the fluid causes it to lag, and hence generate relative motion of the endolymph in the SCC.
• Motion of the endolymph results in the bending of the cupula and therefore also bending of the stereocilia of the hair cells.
• Bending of the stereocilia results in depolarization or hyperpolarization that is a function of the head motion.
Canal Planes

- Canals work in push-pull
- Lateral canals are tilted up 30deg
- Vertical canals are 45deg off midline
- Left AC is parallel to Right PC
- Canals are roughly aligned with EOM planes

Push-Pull Action of the VOR

- LC are excited by movement toward the ampulla while AC and PC are excited by movement away from the ampulla
- Push-pull pairs
  - RLC & LLC
  - RAC & LPC
  - RPC & LAC
- Advantage of push-pull is that in case of disease that destroys one labyrinth, the other side can take over (e.g., ear infection)
Vestibular Nerve

- Vestibular nerve carries information to the vestibular nuclei
  - Regular afferents
  - Irregular afferents
- Anterior and Lateral canal, utricle $\rightarrow$ Superior Division of VN
- Posterior canal, saccule $\rightarrow$ Inferior division of VN
- Information encoded is related to head velocity

Afferent Projections to Vestibular Nuclei

- Four Vestibular nuclei
  - Superior
  - Inferior (Descending)
  - Medial
  - Lateral
- Considerable complexity and redundancy in arrangement of canal projections to VN
Central Projections – Horizontal Canal

Central Projections – Anterior Canal

AC – upward and torsion
Central Projections – Posterior Canal

VOR muscle simulator

• (open in separate window)
Otoliths transduce linear head motion and gravity

- Utricles and Saccules
- Utricles primarily sense tilt (gravity)
- Saccules primarily sense linear acceleration
- Saccule is parasagittal; Utricle is horizontal

- Macula are the equivalent of the cristae and contain hair cells
- Hair cells in the macula are oriented in various directions
- Processes are embedded in otolithic membrane
- Calcite crystals called otoconia are strewn on otolithic membrane
- Saccule – lateral SVN; Utricle – laterodorsal MVN and ventrolateral SVN
Vestibulo-cerebellum

- Flocculo-nodular lobe is the vestibulo-cerebellum
- Receive projections from various vestibular nuclei
- Canal cerebellar projections
  - Flocculus
- Otolith Cerebellar projections
  - Saccule: nodulus/uvula
  - Utricle: nodulus/uvula, flocculus/ventral paraflocculus

Basic Horizontal and Vertical VOR properties

- Visual information is not required for VOR function even though the aim is to provide gaze stability for clear vision
- Characterized by Gain and Phase
  - Gain = Eye Velocity/Head Velocity
    - Normally between 0.8 and 0.9 in humans
  - Phase = Phase difference between eye and head velocity
    - Normally 180 degrees
Vestibular Nystagmus (VN)

- Sustained head rotation results in VN
- Vestibular imbalance can cause VN
- Reducing a signal from one canal is responded to as if the opposing canal were being stimulated
- Eyes drift toward side with lesion.

Basic Horizontal and Vertical VOR properties

- Latency = Time delay between head motion and compensatory eye movements
  - Normally 7-12 ms

- SCC time constant = 5secs

- VOR time constant = 15secs
  - due to velocity storage
  - commissural connections are important
Bode plot of VOR performance

- During locomotion head frequency is 1-5 Hz and head velocity is <150 deg/sec
- VOR performance is optimal for these stimuli

Vision and the VOR

- In resting state VOR gain is about 0.8-0.9
- In the presence of a visual target, gain goes up to 0.95-1.00
- This visual enhancement is believed to be due to the SP/OKN system
- This is called the visually enhanced VOR (Vis-VOR)
VOR Plasticity

- An example of adaptive motor learning capability of the brain
- Must adapt to spectacle correction because they induce rotational minification (myopia) or magnification (hyperopia)
  - Myopes wearing glasses have VOR gain < 1
  - Hyperopes wearing glasses have VOR gain > 1
- Reversing prisms experiment
- Cross-axis adaptation
  - Due to convergence in the vestibular nuclei

VOR Gain is Plastic

- Adaptation can be induced by sinusoidally rotating subject as they view through magnifying or minifying prisms.
- Adaptation occurs in 1-2 hrs
- Cerebellar and brainstem mechanisms calibrate long-term VOR performance
Long term adaptation

- Wearing magnifying or minifying spectacles can change VOR gain over the course of days.
- Consistent effect with different animals and multiple repetitions.

Vestibular Compensation

- Recovery from damage to the labyrinth is called vestibular compensation.
- In humans, it can be due to antibiotic treatment of an ear infection.
- Immediately post lesion, there is a spontaneous nystagmus towards the side of the lesion which goes away over a few days.
- Dynamic VOR gain is reduced by about half.
- Vision immediately post-lesion is critical for compensation.
- Occipital lobe lesion prevents compensation.
VOR and aging

- Drastic reduction of hair cells with age
- People above 75 have 50% of hair cells intact
- Deterioration mostly in low frequency characteristics
- Adaptive mechanisms keep VOR intact in frequency range of interest
- As head velocity increases, even the high frequency response deteriorates

Benign Paroxysmal Positional Vertigo (BPPV)

- 20% of dizziness is due to BPPV; 50% in older people
- Sudden onset of dizziness following some type of minor head injury, migraines; Otherwise idiopathic.
- It is easily recognized by the pattern of dizziness that is brought only when the head is placed in certain positions
BPPV

• Minor head trauma results in the dislodging of the Otoconia from its membrane
• The otolithic debris gets into the semicircular canal, coalesces and tends to interfere with the flow of endolymph.
• The coalesced debris can move around in the endolymph simply under the influence of gravity.
• So vestibular nystagmus can occur even in the absence of head rotation resulting in the sensation of dizziness

How to treat BPPV

• Move otoconia out of the canal and back into the utricle!!
• Posterior canal is the most often affected in BPPV
• Usually only one side is affected
• Epley maneuver – Canalith Repositioning Procedure