Vestibular Physiology
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OBJECTIVES

After studying the material of this lecture, the student should be able to:

1. Describe the structure and function of the vestibular organs.
2. Compare and contrast the statolithic organs (utricle and saccule) with the statokinetic organs (semicircular canals).
3. Explain the difference between the slow and rapid components of nystagmus.
4. Give an example of a vestibular reflex.
5. Describe two clinical tests used to evaluate vestibular function.
6. Define vertigo.

I. VESTIBULAR SYSTEM

Equilibrium or balance is maintained by the vestibular system. This system operates reflexively to coordinate movements and balance of the head, body, and limbs. It is critical for the maintenance of upright posture in environments where there is a constant gravitational force. Vestibular function is particularly important for activities such as gymnastics, figure skating, scuba diving, skiing and other sports where there is coordination and orientation of the body in three dimensional space.

II. PERIPHERAL SENSE ORGANS

A. LOCATION

The vestibular organ is located within the temporal bone adjacent to the auditory sense organ (the cochlea). It is a membranous labyrinth consisting of two subunits: the macula (utricle and saccule) and the semicircular canals. The vestibular organ has two fluid filled compartments: an inner compartment filled with endolymph and an the outer compartment filled with perilymph.
B. MACULA (Statolith Organs)

On each side of the head there are two maculae. These maculae are sensitive to translational (linear) accelerations of which gravity is a special case. Within the macula is an otolith mass made up of mucopolysaccharide and deposits of calcium carbonate (calcite crystals). This mass lies over the sensory hair cells like a Pillow. Forces of inertia (force $= \text{mass} \times \text{acceleration}$) cause the otolith mass to slide across the sensory hair cells bending the stereocilia in direction towards or away from the kinocilia. Displacement towards the kinocilia causes depolarization (excitation) of hair cells and displacement in the opposite direction causes hyperpolarization (inhibition).

![Diagram of the Macula and its response to head tilting](image)

**Figure 2:** Diagram of the Macula and its response to head tilting

The macula within the utricle is oriented horizontally when the head is in an upright position, the saccule is in a vertical position. The orientation of kinocilia on the surface of the macula (utricle and saccule) determines its response properties. In the case of the utricle, tilting the head forward or laterally causes excitation of the ipsilateral utricle. Tilting the head backward or medially causes a decrease in activity. The saccule responds to head movement in all directions. Saccular activity increases with both forward and backward movements (pitch) as well as lateral and medial movements (roll). In addition, the saccule responds to both upward and downward vertical displacements of the head.
The bilateral arrangement of the statolith organs make it possible to encode every possible orientation of the skull. For each position there is a unique constellation (pattern) of activity associated with the nerve fibers innervating the different macula. Thus the pattern of nerve activity from the statolith organs provides information about the position of the head in space.

C. SEMICIRCULAR CANALS (Statokinetik Organs)

There are three canals on each side of the head. They are oriented approximately perpendicular to one another thereby covering the three principle axis of rotation.
The adequate stimulus for the semicircular canals is rotational (angular) acceleration. Each canal consists of a closed fluid filled tube with an enlargement (ampulla) at one end containing the sensory receptor cells. Above the receptor hair cells lies a gelatinous membrane called the cupula. The cupula spans the cross sectional area of the canal and is similar in specific gravity to the surrounding endolymph. Because of this similarity the cupula (unlike the otolith mass) does not move with respect to the canal during translational or linear acceleration. However, during angular accelerations (or rotation) the cupula does move.

When the skull begins to turn or rotate there is an initial period of time during which the endolymph within the canal moves more slowly than the labyrinth. The cupula is attached to the wall of the canal and is therefore dragged through the endolymph causing it to stretch in the direction opposite to the direction of rotation. This stretching of the cupula bends the cilia of the receptor cells causing a change in nerve discharge rate. Displacement of the cupula toward the utricle (midline) causes an
increase in discharge rate and displacement away from the utricle (lateral) causes a decrease in discharge rate. When there is an increase in activity from the left horizontal semicircular canal there is corresponding decrease in activity from the contralateral (right) horizontal canal.

When the rotation reaches a constant velocity the endolymph eventually catches up with the bony labyrinth and the cupula returns to its resting state. If the rotation is suddenly stopped (deceleration) the endolymph fluid continues to move in the direction of rotation for a period of time. This causes the cupula to be displaced in the direction of the initial rotation.

The semicircular canals are arranged perpendicular to one another so as to represent rotations about the three primary axis. A horizontal canal (actually tilted at a 30 degree angle) for rotations to the right or left, an anterior vertical canal for rotations forward and to one side, and a posterior vertical canal for rotations backward and to one side. In addition to these primary axis it is possible for the vestibular system to detect rotation about any axis by monitoring the constellation of nerve discharges from each of the six different semicircular canals. **Thus the semicircular canals**
function to detect and measure angular accelerations around any axis in three dimensional space.

III. CENTRAL CONNECTIONS

The primary afferents of the vestibular nerve terminate in the medulla in a region containing the vestibular nuclei, there are four different vestibular nuclei: the superior (Bechterew's nucleus), medial (Schawalbe's nucleus), lateral (Deiter's nucleus) and inferior (Roller 's nucleus).

The medial and superior vestibular nuclei receive input primarily from the semicircular canals. They in turn project via the medial longitudinal fasciculus to innervate the extraocular muscles. The lateral vestibular nuclei receive input primarily from the utricle and project to spinal cord motoneurons via the lateral vestibulospinal tract. These projections play an important role in maintenance of postural reflexes. Finally the inferior vestibular nucleus receives its input from the utricle, saccule and semicircular canals. It projects via media longitudinal fasciculus to neurons in the brainstem and the cerebellum.

In addition to receiving input from the vestibular organ the vestibular nuclei also get input from muscle and joint receptors in the neck. This input is important because the head is moveable at the neck and the angle of the head with respect to the trunk is also required to determine the position of the body in space.

IV. VESTIBULAR REFLEXES

The vestibular reflexes responsible for balance and coordination of movement in space can be classified into static and statokinetic reflexes.

A. STATIC REFLEXES

The macula organs provide the primary input for static reflexes. These reflexes are responsible for upright posture and position of the limbs in three dimensional space. An example of a static reflex is the compensatory eye rolling response which occurs when the head is tilted toward a horizontal position. The eyes roll in the direction opposite the head tilt in order to keep the pupils in a vertical position. This ensures that horizontal and vertical oriented objects maintain an oriented image on the retina.

B. STATOKINETIC REFLEXES

Statokinetic reflexes can be elicited by the macula or semicircular canals and occur during movement. A classic example is the turning of a cat during free fall so as to land on its feet. Another example is the "lifting response" where extensor tonus is decreased during lifting and is increased during a free fall.
C. **VESTIBULAR NYSTAGMUS**

Nystagmus is a statokinetic reflex in response to an angular (rotational) acceleration in which the eyes initially move against the direction of rotation in an attempt to maintain a particular direction of gaze (slow component). When the eyes approach the limit of lateral movement there is a rapid movement in the direction of rotation (rapid component) where by the eyes jump ahead and fix on a new position in space. **Clinically the direction of nystagmus is defined by the rapid component.** In addition to the vestibular reflex passive rotation produces movement of the visual field resulting in what is known as "optokinetic nystagmus". Both vestibular and optokinetic nystagmus act synergistically.

V. **CLINICAL TESTS OF VESTIBULAR FUNCTION**

A. **BARANY TEST**

The subject is seated on a rotating chair (Barany chair) and turned at a constant velocity (once every 2 seconds) for about 10 revolutions. If the head is tilted forward approximately 30 degrees (horizontal canal) then the eye movements (nystagmus) will be from side to side. If the head is tilted 90 degrees toward one of the shoulders (vertical canals) then the eye movement will be up and down. **In testing the horizontal canals during rotation to the right a "right nystagmus" will be observed. However, if the rotation is stopped abruptly, a "postrotary nystagmus" will be observed in a direction opposite to the direction of rotation.** To avoid visual fixation and measurement of optokinetic nystagmus special glasses are used to make the subject myopic (unable to fixate). During Post rotary nystagmus a subject will tend to turn or fall in the direction of the rotation. This is the result of contralateral stimulation of the extensor muscles since the subject "thinks" he is spinning in the opposite direction.

B. **CALORIC TEST**

By using thermal stimulation it is possible to test the right and left horizontal canals separately. In this test the head of the subject is tilted back 60 degrees. This places the horizontal canals in an approximate vertical position.

The outer edge of the horizontal canal is very close to the external auditory meatus thus by rinsing the ear with warm or cold water heat transfer can be used to cause the endolymph to rise or fall. This produces a flow of endolymph and a deflection of the cupula (i.e. caloric nystagmus). **Warm water produces nystagmus toward the treated side, cold water produces the opposite.** Caloric nystagmus normally lasts about 2 minutes. Shorter periods of nystagmus are suggestive of a vestibular disorder.
VI. DISORDERS OF THE VESTIBULAR SYSTEM

A. **KINETOSIS (motion sickness)**

Strong stimulation of the vestibular system often results in unpleasant sensations such as dizziness, sweating, nausea, and vomiting. Kinetosis results when one is unaccustomed to a particular vestibular sensation (rocking motions in flight or at sea) or when there is a discrepancy between sensory inputs (reading while traveling on a bumpy road).

B. **VERTIGO**

*Vertigo is the sensation of rotation or dizziness in the absence of movement.* Vertigo can occur in patients with vestibular damage following trauma, infection, vascular occlusion and after exposure to some toxic chemicals. Ménière's disease is a condition in which there are severe attacks of vertigo, nausea and vomiting. There is also a progressive unilateral deafness and tinnitus (ringing sensation) associated with Ménière's disease.

**ADDITIONAL REFERENCES**
