Auditory & Vestibular Systems

The 8th cranial nerve provides for hearing and balance of the head – vestibulocochlear nerve. It divides into two portions: vestibular & cochlear.

Outer Ear (Nolte 5th Ed pp 342 Netter Plate 88)

The outer ear is what we can see. It is composed of the auricle and the external auditory meatus. The external auditory meatus leads inside to the tympanic membrane where sound vibrations are conveyed to.

Middle Ear (Nolte 5th Ed pp 343 Netter Plate 88/89)

Sound induced vibrations of the tympanic membrane are transferred along to a chain of three small bones called ossicles. The ossicles are located in the middle ear cavity – an air filled cavity in the temporal bone. The ossicles are: malleus, incus, and stapes. The malleus is attached to the medial surface of the tympanic membrane, so vibrations are directly transferred. The malleus is in turn attached to the incus, which is attached to the stapes. So sound induced vibrations reach the stapes. There are two small muscles which are attached to the middle ear bones that modulate the sound signals transmitted to the inner ear. These are: tensor tympani (V) & stapedius (VII). When these contract, they reduce the transmission of vibration through the ossicular chain (i.e: through ossicles). The stapes is situated in a hole in the temporal bone called the oval window. The main function of the middle ear is to amplify the sound induced vibrations from the tympanic membrane. This means a given vibratory force at the tympanic membrane results in a slightly greater force at the stapes (i.e.: more force per unit area due to stapes being 15 times smaller than tympanic membrane). The Eustachian tube (auditory tube) connects to the pharynx.

Inner ear (Nolte 5th Ed pp 338 Fig 14-3 Netter Plate 90)

The bony labyrinth is a system of cavities in the petrous part of the temporal bone. This system of cavities is filled with perilymph. The bony cochlea extends anteriorly from an enlargement called the vestibule. The bony semicircular canals are attached to this vestibule. The composition of the perilymph is quite similar to CSF, high in Na^+, low in K^+. The subarachnoid space is actually continuous with the perilymphatic space via a small canal.

Inside the bony labyrinth, there is a membranous labyrinth. It follows the same pathway as the bony labyrinth. Within the cochlea, there is cochlear duct, within the semicircular canals, there is are semicircular ducts. Unlike the bony labyrinth, which contains a single enlargement: vestibule, the membranous labyrinth consists of two enlargements: utricle (connected to the semicircular ducts) and the saccule (connected to the cochlea duct).

The membranous labyrinth is filled with endolymph, which is similar in ionic composition to intracellular fluids (high in K^+ and low in Na^+). Thus the endolymph flows in a closed system of canals/cavities. The walls of the membranous labyrinth consist of hair cells joined together by tight junctions. This acts as a diffusion barrier with the perilymph. Much like the CSF, endolymph is produced by an active pumping mechanism (producing the + positive with respect to the perilymph) and reabsorbed. Endolymph is produced by the stria vascularis, it circulates within the ducts and accumulates in the utricle (semicircular ducts) and saccule (cochlear duct). From here, two ducts join in a Y shape arrangement to form the endolymphatic duct in vestibular aqueduct, which drains into the endolymphatic sac.

Cochlea + Sound transduction (Nolte 5th Ed pp 340 Fig 14-12 Netter Plate 87)

The cochlea is an anterior enlargement from the vestibule of the bony labyrinth. It is a snail shaped structure, 2.75 turns. It houses the organ of Corti and is involved in sound transduction. The vibration is transmitted along the external auditory meatus, reaches the tympanic membrane, and is transferred along the ossicles. It reaches the stapes, which is intimately associated with the oval window of the bony labyrinth. If the membranous labyrinth is taken out, leaving the bony labyrinth intact – the canals are called scala vestibuli. Thus, vibrations are transferred to the perilymph (this is now displaced → ripples) filling the scala vestibuli (Netter Plate 87). Vibrations reach the helicotrema, where it communicates with the scala tympani (Netter Plate 90). The scala media is the space enclosed by the cochlear duct. The energy passing from the scala vestibuli to scala tympani deforms the cochlear duct (scala media). This deformation travels as a wave/ripple along the basilar membrane*. The basilar membrane forms the floor of the cochlear duct, separating it from the scala tympani.

The organ of Corti is a strip of hair cells and supporting cells resting on the basilar membrane. The hair cells form two major groups. The inner hair cells – about 3000, and outer hair cells – about 15000. The two groups are separated by a space called tunnel of Corti, which transmits peripheral processes of the 8th cranial nerve to the outer hair cells (Fig 14-12 of Nolte 5th Ed pp 349). The hair cells have a special arrangement. They consist of stereocilia on one end projecting into the endolymphatic space, whilst the other end receives innervation from 8th cranial nerve fibres (Fig 14-4 pp 341). The stereocilia of outer hair cells are embedded into a gelatinous mass called tectorial membrane. Thus vibrations cause displacement of the basilar membrane*, causes oscillations of the hairs (stereocilia) therefore each hair falls on another. The tip links (extend from one stereocilium to its neighbouring one) are displaced, which trigger opening of K^+ channels (Fig 14-6/14-7 pp 343/344). K^+ ions influx from endolymph. This depolarizes the cell membrane, further opening voltage gated Ca^{++} channels. Ca^{++} influx occurs, and these causes the release of neurotransmitter glutamate at the other side of the hair cell. Anatomical evidence suggests inner hair cells are not embedded in a tectorial membrane, and that they can be stimulated directly by movement of endolymph within the cochlear duct. Glutamate binds to the sensory afferent endings of the cochlear nerve (VIII). Deflecting the hair bundle in the opposite direction (large sterocilium to small) will close the K^+ channels, the hair cell hyperpolarizes, Ca^{++} influx reduced, and glutamate release diminishes. This reduces the firing rate of the afferent cochlear fibres (VIII). The cell bodies of these afferent cochlear fibres are located within the spiral ganglion.

Note that one inner hair cell will synapse with many auditory (i.e.: 20) afferent fibres, whilst multiple outer hair cells will synapse with 1 auditory afferent fibre.

3 parameters of sound (Nolte 5th Ed pp 348 Fig 14-10C)

The basilar membrane's mechanical properties change as it extends distally. Note that sound is determined by three parameters. Intensity: coded by the rate of firing of action potentials in nerve fibres, and number of fibres firing (measured in dB). Frequency: base of basilar membrane → low frequency, apex → high frequency. Generally, the whole basilar membrane can pick up low frequency sounds. This difference in sensitivity is due to the width and rigidity of the basilar membrane → **tonotopicity**. The base is 100um wide and relatively rigid (most sensitive to high frequency), whilst the apex is 500um wide and relatively floppy (most sensitive to low frequency). The human ear is most sensitive to 3000Hz. The location of the sound is determined by the comparison of sounds reaching the two ears; this is done in the CNS (superior olivary nucleus).

Central auditory pathway (Nolte 5th Ed pp 351 Fig 14-18A)

Auditory primary afferents pick up the signals from the hair cells, and travel to the pontomedullary junction (via spiral ganglion – where cell bodies of 1^0 afferents located). Here, each fibre branches into two innervating the dorsal and ventral cochlear nucleus. The cochlear nuclei are located on the dorsal and lateral aspect of the inferior cerebellar peduncle. Some fibres from the cochlear nuclei cross the midline, with a slight rostral inclination and join the lateral lemniscus. The lateral lemniscus runs on the lateral aspect of the tegmentum of the pons (roof). A small number of efferent fibres from the cochlear nuclei do not cross the midline, and join the ipsilateral lateral lemniscus. Thus, auditory information is distributed bilaterally in the CNS. The fibres from lateral lemniscus terminate at the inferior colliculus. The inferior colliculus gives off the brachium of the inferior colliculus, which terminates at the medial geniculate nucleus. Fibres from here, project to the primary auditory cortex (transverse temporal gyri) on the superior surface of the temporal lobe.

A larger number of efferents from the cochlear nuclei terminate in the superior olivary nucleus. These are involved in sound localization. Sound localization can be done via two ways: time of arrival of sound in both ears, intensity of sound in both ears. That is, if sound comes from one side of the head, then that side will experience quicker sound to that ear, and a slightly more intense sound. There are two subsets of superior olivary nuclei – which subserve the two methods of sound localization. The medial superior olive is responsible for time of arrival comparison. This is more efficient in animals like us. So the medial superior olive is relatively large in humans. So fibres from the cochlear nuclei converge at the superior medial olive, for comparison. Fibres from here cross over via the trapezoid body. From here, it joins the lateral lemniscus to the ipsilateral inferior colliculus.

Conductive hearing loss (Nolte 5th Ed pp 356-358)

Conductive hearing loss occurs because airborne vibrations cannot read the organ of Corti, to displace the stereocilia of the hair cells. But, bone sound conduction is normal. This is because sound travels via the bone, to cause the inner ear to oscillate. Another process that can cause hearing loss is by damaging the hair cells, cochlear nerve, or the cochlear nuclei → Sensorineural hearing loss. This causes impairment in hearing, via bone conduction or airborne conduction.

Vestibular System (Nolte 5th Ed pp 358 Netter Plate 90)

The vestibular system consists of: the semicircular canals, and the otolithic organs belonging to the bony labyrinth of the human. The dilation in the central area of the bony labyrinth is the vestibule, which is associated with the three semicircular canals: anterior, posterior, horizontal. Within each semicircular canal, is a semicircular duct of the membranous labyrinth. Within the vestibule are the otolithic organs: utricle and saccule (dilatations of the membranous labyrinth).

Utricle and Saccule (Nolte 5th Ed pp 358)

The utricle and saccule detect linear acceleration and position of the head. Within their walls, they have supporting cells and hair cells (macula). The utricular macula is roughly on the inferior surface of the utricle, so in a horizontal plane in an upright individual. The saccular macula lies on the medial wall, therefore roughly in a vertical plane. The hair cells of the vestibular system have stereocilia and also kinocilium. The kinocilium is the single true cilium of the macula. The sensory hairs of the macular cells are embedded in a gelatinous membrane (similar to the auditory system) but it contains some calcium carbonate crystals called otoconia. Thus, this membrane is called otolithic membrane. This membrane is gelatinous, so head movements will “flop” it around, stimulating the hair cells (action potential generated in the vestibular afferent fibres) – which signal the new position of the head. The utricular macula is sensitive to linear acceleration – horizontal plane (forward-backward, side to side) and to head tilts beginning from normal position, whilst the saccular macula is more sensitive to linear acceleration – vertical plane (forward-backward, up-down) and to head tilts beginning from sideways position.

Semicircular ducts (Nolte 5th Ed pp 358)

The semicircular ducts detect angular acceleration (rotation of head in any plane) of the head. There are three on each side approximately at right angles to one another. They communicate with the utricle at both ends, but one end has a dilated part called the ampulla. Each ampulla contains the crista, which has supporting cells and sensory hair cells. Like other parts, each sensory hair cells consists of “hairs” composed of a single true cilium and stereocilia embedded in a gelatinous mass → called cupula. Deflection of the cupula will produce a deflection of the stereocilia and therefore a receptor potential is generated. This is transmitted to the vestibular afferent fibres innervating these hair cells, which fires an action potential. Note that deflection in one direction will depolarize the membrane, whilst the other direction will hyperpolarize the membrane.

Central processing of vestibular information (Nolte 5th Ed pp 361 Fig 14-28)

Head movements are detected by hair cells of the utricle, saccule and semicircular canals. An action potential is generated within the primary afferent fibres (sensory), whose cell bodies are in the vestibular ganglion, located in the internal auditory meatus (analogous to DRG in spinal cord). 1^0 fibres project to the vestibular nuclei (made up of 4 nuclei), located on the floor of the 4th ventricle. 2^0 neurons now project to the following areas:

- flucculonodular lobe of the cerebellum
- ipsilateral lateral vestibulospinal tract to all spinal cord levels – brings about postural changes in response to head movements and tilts
- medial vestibulospinal tract bilaterally to cervical spinal cord through the MLF – brings about compensatory neck movements to stabilize our head while walking around, or moving head in space.
- Bilaterally to oculomotor, trochlear, abducens nuclei via MLF
- Reticular formation – influence muscle tone via recticulospinal tract
- Thalamus → cerebral cortex – general perception of equilibrium

Vestibuloocular reflex (Nolte 5th Ed pp 364 Fig 14-30)
Refer to Orbit and control of eye movements lecture. Explained in detail there compared to this lecture.

Nystagmus (Nolte 5th Ed pp 366 Fig 14-31)
Refer to Orbit and control of eye movements lecture as well. The vestibuloocular reflex is there to compensate for head movements, so that we can still fixate on an object. What happens when the head movement is too much for the reflex to compensate? → nystagmus is caused. Nystagmus is named according to the direction of rapid movement (i.e.: left/right beating nystagmus). Physiological nystagmus can be caused by: head movements, endolymphatic convection currents (Caloric nystagmus) & moving visual
stimuli.

Caloric Nystagmus (Nolte 5th Ed 368 Fig 14-31)
Caloric nystagmus is induced physiological nystagmus due to instillation of cold/warm water – head tilted back at 60^0. When you move your head to the left (per say) the convection current developed in the endolymph is clockwise (Refer to Fig 14-25 to visualize this). So instilling cold/warm water into the right ear will produce convection currents of endolymph in a clockwise direction – just like rotating your head to the left. This will induce a left beating nystagmus.