CONCEPTS
1. Audition (hearing), like vision, is one of the most important sensations. Much of human communication depends on a properly functional auditory system.
2. Sound is produced by vibrations that result in the alternate compression and rarefaction (decompression) of air. The pressure waves generated in the air in this manner reach the ear and are transduced into neural signals that are processed in the brain.

LEARNING OBJECTIVES FOR THE AUDITORY SYSTEM
1. Describe the characteristics of a sound wave.
2. Describe and diagram the anatomy and physiology of the external, middle, and inner ear, including the production of endolymph and its chemical makeup.
3. Describe the mechanism of sound conduction and the movement of the pressure wave through the external, middle, and inner ear.
4. Describe transduction of the pressure wave into action potentials by the hair cells found in the Organ of Corti. Be able to differentiate the function of the inner and outer rows of hair cells.
5. Describe and diagram the ascending and descending auditory pathways, including the various relay nuclei and the tonotopic representation of various frequency throughout the auditory pathways.
6. Describe the clinical disorders associated with the auditory system.

Auditory System

Sound is produced by vibrations that cause the alternating compression and decompression of the surrounding air, resulting in the formation of a pressure wave with associated peaks and valleys of varying amplitudes of intensity.

Intensity = dB (logarithmic; 10-120)
- Human speech ~ 65dB
- Frequency = Hz (10-20,000)
Middle Ear
The middle ear is the cavity within the temporal bone (petrous portion) where air pressure waves (sounds) are converted to mechanical energy by means of the tympanic membrane and connecting ossicles. The cavity lies medial to the tympanic membrane, and communicates with the nasopharynx through the auditory (eustachian or pharyngotympanic) tube. It is often the site of mild to severe acute and chronic infections, known as otitis media.
THE AUDITORY OSSICLES

In the middle ear, there are three small bones - malleous, incus and stapes - joined to each other by true synovial (diarthrodial) articulations. They are covered by the mucous membrane lining the tympanic cavity (NO periosteum) and are suspended in the tympanic cavity by ligaments. They function to convert vibrations of air (sound waves) reaching the tympanic membrane into mechanical energy, which results in the oscillation of the stapes at the oval (vestibular) window. The perilymph of the cochlea is displaced, thus stimulating the sensory endings on the hair cells of the spiral organ (of Corti).

The ossicles are fixed in position by the attachment of the malleous to the tympanic membrane and by the stapes in the oval window. Various other ligaments also connect the ossicles to the walls of the tympanic cavity.

Movement of the Ossicles

Pressure Wave

Middle Ear – Lateral Wall
**Stapedius and Tensor Tympani Muscles**

Stapedius
- Innervated by CN VII
- Originates from pyramidal eminence and attaches to neck of stapes
- Prevents excess movement of the stapes, helping to control the amplitude of sound waves from the general external environment to the inner ear. (Paralysis of the stapedius allows wider oscillation of the stapes, resulting in a heightened reaction of the ossicles to sound vibration; this condition, known as hyperacusis, causes normal sounds to be perceived as overly loud)

Tensor Tympani
- Innervated by CN V (specifically a branch of V3)
- Originates from Eustachian tube and attaches to handle of the malleus.
- Contraction of the tensor tympani muscle tightens the ear drum and dampens sound, typically in loud environments (airport, rock concert, etc.)
**Inner Ear**

The inner ear is composed of the bony and membranous labyrinths.

- The bony portion is filled with **perilymph**, which is continuous with the fluid surrounding the vestibular system.
- The membranous portion is filled with **endolymph**, which is also continuous with the structures in the vestibular system (semicircular canals, etc.).
Transduction of pressure waves to the inner ear can be by one of three routes:

1. **Air** - poor conduction; most (95%) reflected off of round window (largely ignored).
2. **Osseous** - due to vibration of bones (mastoid & petrous) in skull; large loss of energy (typically referred to as "Bone Conduction").
3. **Ossicular** - MOST EFFICIENT due to direct coupling between inner structures and outer ear canal (typically referred to as "Air Conduction" by physicians).

• The "hearing" structure is the cochlea, which is contained within the **modiolus**.
• The cochlea consists of the Scala Vestibuli (oval window) the helicotrema (apex) and the Scala Tympani (round window).
• The cochlear duct (scala media; membranous labyrinth) lies between these two bony channels, and is separated from them by Reisner’s membrane above and the Basilar membrane below.

• The basilar membrane is widest at the helicotrema and stiffest at the base. These properties allow it to respond selectively to different frequencies of sound, with high pitches near the base where it is the stiffest, and low pitches near the apex where it is most flexible.

Between the Reisner’s and Basilar membranes is the Tectorial membrane, which is a highly elastic and acellular (similar to the Basilar membrane). It is anchored along the spiral axis of the modiolus and extends over the Organ of Corti, resting on the apical surface of the inner and outer rows of hair cells.
Sitting on the basilar membrane is the Organ of Corti, where transduction of these pressure waves takes place in the hair cells.

There are 3 outer rows of hair cells and 1 inner row:

- The outer hair cells are displacement sensitive, and highly convergent on the bipolar cells (10 hair cells per bipolar cell); they receive only 10% of the overall innervation of the cochlea. The outer hair cells are long and flexible, and are used to modulate the tectorial membrane. These are the ONLY receptors which can be directly modified by the CNS, and can change their length and stiffness.

The orientation of hair cells is functionally significant:

- The inner hair cells are velocity sensitive, and each are innervated by up to 10 bipolar cells (10 bipolar cells per hair cell); they receive 90% of the overall innervation of the cochlea. The inner hair cells are short and stiff, and are used primarily to detect sound. They are NOT directly modified by the CNS. Due to the unique innervation ratio of the inner hair cells, each nerve fiber has a characteristic frequency of excitation based on it's position on the basilar membrane.
The first action potential is in the bipolar cells, not the hair cells.

Due to its differences in stiffness and in width, the basilar membrane resonates at different frequencies along its length. These differences are what give the nerve fibers their characteristic frequency of excitation, and the "Tonotopic Map" of the basilar membrane. This tonotopic organization is then carried through to all other levels of the CNS, including the cochlear nuclei, inferior colliculus, medial geniculate and the cerebral cortex itself (Heschel's gyrus; primary auditory cortex).
**Functional Auditory Pathways to the CNS**

- **DCN**: Dorsal Cochlear nucleus
- **PVCN**: Posterior Ventral Cochlear nucleus
- **AVCN**: Anterior Ventral Cochlear nucleus
- **LSO**: Lateral Superior Olivary nucleus
- **MSO**: Medial Superior Olivary nucleus
- **TB**: Trapezoid Body
- **NLL**: Nucleus of the Lateral Lemniscus
- **IC**: Inferior Colliculus
- **MGB**: Medial Geniculate Body (Thalamus)

**Auditory Pathways**

- **CN VIII**
- **ICP**
  - “Saddlebags” hanging over the ICP
Temporal resolution is achieved by "phase locking" of the hair cells and bipolar cells; they fire a burst of APs at the initiation of the sound and cue in the CNS as to the onset of the new stimulus; they also hyperpolarize at the offset.

Perception of Sounds

Localization of sounds is interpreted by the CNS through a combination of 2 methods:

1. Due to our bilateral hearing structures, sounds lateral to our ears will reach one ear before the other, with a maximal temporal delay of ~50 μs. This delay is called the "interaural difference" and can be interpreted by the CNS to localize where a sound is coming from.

2. We can also localize sounds by changes in pitch and intensity. As sounds move toward us, the intensity and pitch increase; as they move away, the intensity and pitch decrease (think of a train whistle as it passes by).

Interpretation of Auditory Input: Language
This model of the wiring pattern for language makes several predictions possible:

1. Lesions in Wernicke's area will result in failure to comprehend the auditory signals, and if the lesion extends posteriorly into the PTO (association areas), then visual input for language may also be affected. The patient will be unable to understand either visual or spoken language.

2. Lesions in Broca's area will not affect comprehension or formation of language, but will cause a major disruption of speech output and the verbal production of language, due to the loss of input to the motor cortex.

3. Lesions of the arcuate fasciculus will also disrupt verbal output.

There are four types of hearing loss:

- **Auditory Processing Disorders**
- **Conductive**
- **Sensorineural**
- **Mixed**

**Auditory Processing Disorders** occur when the brain has problems processing the information contained in sound, such as understanding speech (Wernicke’s Area) and working out where sounds are coming from (Primary Auditory Cortex).

**Conductive Hearing Loss** occurs when there is a problem with the Outer or Middle Ear which interferes with the passing of sound to the Inner Ear. It can be caused by such things as too much ear wax, ear infections, a punctured eardrum, a fluid build-up, or abnormal bone growth in the Middle Ear (such as Otosclerosis). It is more common in children (ear infections) and indigenous populations. Surgery and some types of hearing technologies can be used to treat Conductive Hearing Loss such as Bone Conduction Hearing Aids, Bone Anchored Hearing Devices and Middle Ear Implants.

**Sensorineural Hearing Loss** occurs when the hearing organ, the Cochlea, and/or the auditory nerve is damaged or malfunctions so it is unable to accurately send the electrical information to the brain. Sensorineural Hearing Loss is *almost always permanent*. It can be genetic or caused by the natural aging process, diseases, accidents or exposure to loud noises, such as Noise-induced Hearing Loss and certain kinds of chemicals and medications. Auditory Neuropathy is another form where the nerves that carry sound information to the brain are damaged or malfunction. Technologies such as Hearing Aids, Cochlear Implants and Hybrid Cochlear Implants can help reduce the effects of having Sensorineural Hearing Loss.

**Mixed Hearing Loss** occurs when both Conductive Hearing Loss and Sensorineural Hearing Loss are present. The sensorineural component is typically permanent, while the conductive component can either be permanent or temporary. For example, a Mixed Hearing Loss can occur when a person with Presbycusis* also has an Ear Infection.

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* Presbycusis is the most common type of Sensorineural Hearing Loss caused by the natural aging of the auditory system. It occurs gradually and initially affects the ability to hear higher pitched (higher frequency) sounds.
Shel Silverstein and the Auditory System:

DIES A TREE FALLING ON A FOREST, MAKE ANY NOISE?

A bit of Farside humor . . . .

Professor Wainwright's painstaking field research to decode the language of bears comes to a sudden and horrific end.

And Calvin said it best . . . .
I ate too much